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ANALYSIS OF ARIZONA ARRESTOR BED PERFORMANCE

Special Report

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The Arizona Department of Transportation (ADOT) designs arrestor beds using an equation that predicts stopping distance based on entry velocity, assumed rolling resistance (R), and the slope of the bed. There are several arrestor bed features not accounted for in the design equation that are specified based on experience: 1) bed depth, 2) length of transition from initial depth to final depth, and 3) aggregate specification. The arrestor bed design equation has been cited as overly conservative in research done by the Pennsylvania Transportation Institute (PTI). Additionally, ADOT is interested in the effect of different types of equipment that can be used to level and scarify the bed after an entry.

To evaluate Arizona arrestor bed performance, ADOT performed 102 full scale truck entries distributed among four of Arizona's seven arrestor beds. Testing approximated a 2x2x3 factorial experiment. The length of each run was measured and recorded. The velocity during most of the runs was recorded every 1/20 th of a second by a radar gun connected to a data recorder. The stopping distance and a back-calculated R value were used as response variables for Analysis of Variance (ANOVA). The time vs. velocity plots were used to determine the character of the deceleration of each run.

The analysis indicates that stopping distance increases approximately 70% when entry velocity is increased from 45 mph to 65 mph. Runs in the tracks left by a previous entry increased stopping distance by approximately 14%. An equipment type that is capable of scarifying the bed will decrease the stopping distance approximately 17% over equipment types that only levels the bed. At the highest design entry speed, in beds of comparable aggregate and slope, an average R value of 0.41 was achieved in a bed that had an average depth of 39.2 inches over the average stopping distance, and an average R value of 0.34 was achieved in a bed that had an average depth of 12.8 inches over the average stopping distance.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

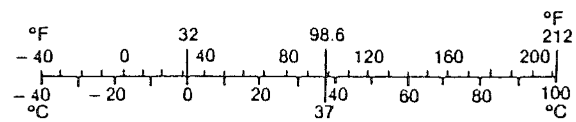
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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INTRODUCTION

Gravel arrestor beds are the most common of all runaway truck arresting schemes. They have been used in the United States for approximately 35 years (1,2). Gravel arrestor beds are designed and maintained based on experience. The most common equation for predicting stopping distance was originally derived to model the speed of trucks climbing long grades. Later it was modified to predict stopping distance in arrestor beds (3,4,5). The equation uses an energy balance to account for the tire-aggregate interaction loss by a "rolling resistance" factor. There has been some question as to whether this is an adequate model for arrestor beds. The equation is given below:

$$L = \frac{V_i^2 - V_f^2}{30(R+G)} \qquad (1)$$

Where:

L = Length Traveled (ft)

V_i = Initial Velocity (mph)

V_f = Final Velocity (mph)

R = Rolling Resistance

G = Grade (percent divided by 100)

The constant in equation (1) is equal to 2 times the acceleration due to gravity, 32.2 fps, divided by 1.467^2. This last term converts velocity from miles per hour to feet per second.

The Arizona Department of Transportation (ADOT) began building gravel truck escape ramps in the early 1980's. ADOT designs have been altered with respect to the length, aggregate specification, and aggregate depth. The required length of arrestor beds was estimated using equation (1) with an entry speed of 90 mph and a rolling resistance factor of 0.25. The aggregate specifications were altered to require a 1 inch nominal maximum size uniformly graded aggregate. The depth of aggregate was increased to a minimum of 36 inches and a transition zone was incorporated into the design to gradually change the depth from 6 inches to 36 inches. For example, the 1-17 south bound arrestor bed transitions from an initial depth of 6 inches to 24 inches in 400 feet, then at 900 feet there is a 200 foot transition to 36 inches. As a result of the increased length, tighter aggregate specifications, and greater depths, the cost of arrestor beds greatly increased.

The concern over the lack of performance of some in-service arrestor beds to stop trucks, and the subsequent high costs of the conservative escape ramp designs were a source of concern for ADOT. In 1987 the Pennsylvania Transportation Institute (PTI) released information from a large research program on gravel arrester beds. Initial results indicated equation (1) was overly conservative and a new mechanistic model might give better predictions.

The concern over the performance of existing arrestor beds and the new information by PTI prompted ADOT to initiate research on the performance of Arizona arrestor beds. In 1989, ADOT contracted with Arizona State University (ASU) to perform arrestor bed research. The ASU researchers designed and fabricated equipment for measuring time-velocity records of vehicles stopping in an arrestor bed (6), performed tests on the material characteristics of the aggregates in the arrestor beds, and collected data on 102 entries into four of Arizona's arrestor beds.

Objective

The objective of this project was to evaluate Arizona arrestor bed performance based on the 102 full scale test runs that were made. Experimental data were used to determine if equation (1) is a suitable predictor for arrestor bed design and if so, what R value should be used. The experimental data was also used to make inferences about the following arrestor bed design and maintenance features:

1. Bed depth,
2. Required length of transition from initial to final depth,
3. Aggregate specification, and
4. Arrestor bed maintenance equipment.

Scope and Limitations

The aim of this study was to determine the effect of gravel arrestor bed design parameters and maintenance practice on performance. The study focused on full scale testing in four Arizona arrestor beds using an articulated tractor with a flat-bed trailer at two entry speeds, 45 and 65 mph, as well as three types of bed maintenance equipment. The study was limited by the existing geometry of the beds, the gravel types in place, and the gravel depths. All Arizona arrestor beds have a gravel-depth gradient. Two of the beds tested have variable grades. The change in depth and simultaneous change in grade complicates the objective of determining the effect of gravel depth. The differences in the design of each of the arrestor beds limits the possible inferences of the experiment with respect to arrestor bed design variables. For example, direct comparisons are not possible on the effect of either bed depth or aggregate characteristics from the data that could be collected during this project.

LITERATURE REVIEW

There are several sources available on vehicle arresting systems, basic arrestor bed research, and arrestor bed pilot testing by transportation agencies. One literature source on truck arresting schemes that contains a derivation of an arrestor bed length predicting equation is reviewed. Three literature sources about basic arrestor bed research, one done in England in the 1960's, one done in Australia in the mid 1970's, and one done in Pennsylvania in the mid 1980's are summarized. The description of several arrestor bed pilot testing programs by state agencies are briefly described. Finally, one literature source on aggregate freezing and contamination is reviewed.

Vehicle Arresting Schemes

Jones explored various truck arresting schemes including (8):

- Chain Arrestor,
- Inertia Wheel Arrestor,
- Arrestor Engine Brake,
- Hydraulic Arrestor, and
- Passive Arrestor.

Of all the truck arresting systems reviewed, only the gravel arrestor bed performs independent of vehicle weight. Active arresting systems are designed to dissipate a certain amount of kinetic energy. For a given entry velocity, vehicles of different weight have different amounts of kinetic energy. If an active arresting system is designed to safely stop an 80,000 lb truck entering at 90 mph, then a vehicle of lesser weight or velocity will be stopped with deceleration forces that could harm the passenger. This problem can be overcome by designing a series of energy dissipators, however this approach is extremely expensive (9). Jones states that the friction coefficient of gravel arrestor beds depends on vehicle characteristics such as the number of wheels, tire floatation, tire tread style, height of trailer bed, and fender style, but is independent of vehicle entry velocity and weight.

Derivation of Arrestor Bed Model

Jones uses Newton's second law to derive an equation that predicts stopping distance in gravel arrestor beds equivalent to equation (1). The derivation is given below:

$$F = ma$$

$$= \frac{W}{32.2} a$$

Where:

F = Decelerating Force

m = Vehicle Mass,

W = Vehicle Weight, and

a = Vehicle Acceleration

Assuming the action of the gravel is frictional resistance (4):

$$F = \mu W$$

Where:

μ = The Friction Coefficient

Then:

$$\mu = \frac{a}{32.2} \quad \text{.......(2)}$$

To obtain an equation for predicting stopping distance when the friction coefficient is known, equation (2) is integrated, resulting in an equation for velocity in terms of time plus a constant of integration. The constant of integration represents the initial condition, which is the entry velocity. When the entry velocity is inserted into the equation and the dependent variable velocity is set to zero; the time to stop is obtained. The velocity equation is subsequently integrated from zero to time to obtain an equation for stopping distance in terms of time. Figure 1 shows the derivation graphically.

Using a kinematic equation for constant acceleration:

$$V_f^2 = V_i^2 + 2a(X_f - X_i)$$

Letting $L = X_f - X_i$ = Stopping distance, then:

$$L = \frac{V_f^2 - V_i^2}{2 * 32.2\mu} \quad \text{.......(3)}$$

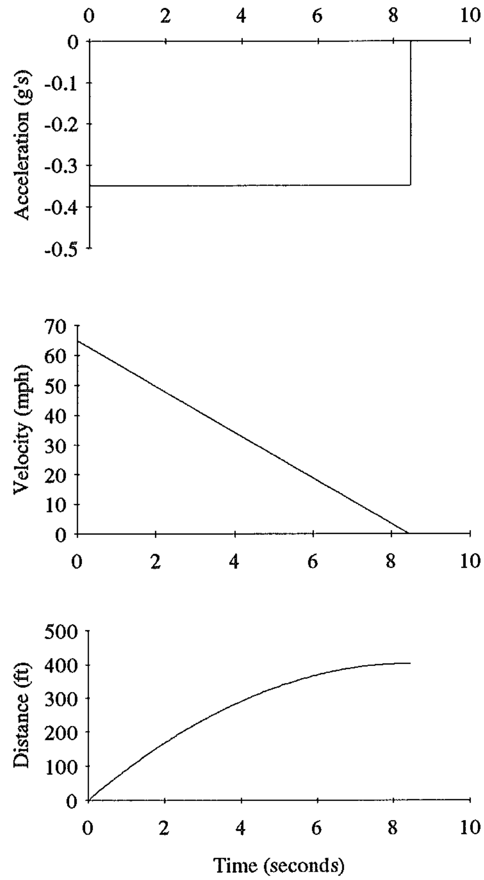


FIGURE 1 JONES'S MODEL FOR 65 MPH ENTRY SPEED, -.35 G ACCELERATION

Comparing equations (1) and (3) demonstrates that the resistance term, μ, in equation (3) is equal to the combination of rolling resistance and grade resistance. Furthermore, for a zero grade arrestor bed, $R = \mu$, and equation (2) shows that $R = a/32.2$. Therefore, for a zero grade arrestor bed, R is the deceleration rate expressed in terms of g.

Jones states the passive arresting scheme, that is gravel arrestor beds, are less expensive to operate and maintain than active arresting schemes. This is true, to some extent; however, as will be shown later, the performance of gravel arrestor beds is dependent upon proper maintenance after each entry. This generally requires a crew of at least two maintenance workers and earth moving equipment such as a bulldozer.

Basic Arrestor Bed Research

Some of the first gravel arrestor bed research was conducted in England by Jehu and Laker (10), and later by Laker (11). In the research by Jehu and Laker, passenger vehicles, an articulated tractor with trailer, and a fire tender were run into beds of lightweight aggregate, and natural-angular aggregate. The lightweight aggregate bed had a constant depth of 24 inches with an aggregate that passed the 3/8 inch sieve and was retained on the 3/16 inch sieve. The natural-angular aggregate bed had variable depth that was 3 inches for the first 15 feet, and increased to 30 inches over the next 45 feet, and remained at that depth to the end of the 380 foot bed. The natural-angular aggregate passed the 3/8 inch sieve and was retained on the 1/4 inch sieve. The bed had a constant depth of 18 inches. For an entry speed of 30 mph, the R value in the lightweight aggregate was 0.58 g, the rounded aggregate produced a R value of 0.6 g, and the R value in the natural-angular aggregate was 0.45 g.

Jehu and Laker concluded from these studies that the deceleration provided by the gravel arrestor beds is dependent on the size and shape of the aggregate, but is substantially independent of the vehicle type or entry speed. Jehu and Laker also concluded that small aggregate produced a higher deceleration. Jehu and Laker comment that gravel beds with a transition from some initial depth to the final depth appear to be less efficient from a vehicle deceleration standpoint. However, as the entry speed increases, the effect of variable depth decreases.

Laker found an average deceleration of 0.50 g and recommends depth should not be less than 15 inches and preferably 18 inches. Using these assumptions, Laker reduced equation (1), for a zero grade arrestor bed, to:

$$L = \frac{V^2}{127} \qquad (4)$$

Where:

L = Required length in meters

V = Entry velocity in km/hr

Shattock conducted arrestor bed testing in Australia to compare the deceleration obtained from local dune sand and local aggregate (12). Two arrestor beds were built to a depth of 17.7 inches, side by side, on a zero grade pavement. One bed was comprised of sand, the bulk of the material passing the 600 μm sieve and retained on the 150 μm sieve. The other was comprised of partly crushed river gravel, the bulk of the material passing the 9.50 mm sieve and retained on the 4.75 mm sieve. Entry speeds ranged from 12.4 mph to 52.8 mph. The vehicles used in the testing were a station sedan weighing 2680 pounds, and a single unit truck weighing 20,000 pounds.

A total of 15 runs were made, 5 in the crushed aggregate and 10 in the dune sand. The mean deceleration of all runs in the crushed aggregate was 0.13 g, and the mean deceleration of all the runs in the dune sand was 0.34 g. The highest speed run in the dune sand, with the station sedan, produced a deceleration of 0.26 g. Shattock describes the character of the run as very little penetration at the beginning of the run, with a middle portion of the run having a good penetration followed by an ending portion with little penetration.

Citing the work of Jehu and Laker, Shattock gives the following equation for predicting stopping distance in a dune-sand arrestor bed:

$$L = \frac{V2}{100+2.54X} \qquad (5)$$

Where:

L = required length in meters

V = entry speed in Km/hr

X = grade in percent

Equation (5) corresponds to equation (1) with a R value of 0.4 g. Shattock states that although the mean deceleration in dune-sand is 0.34 g's, designs can be based on 0.4 g's since traffic entering the bed for emergency use will be traveling at a higher speed and will therefore have a higher rolling resistance factor. Shattock concludes by stating that stopping distance is directly dependent on entry speed and independent of vehicle type or weight.

One of the most extensive arrestor bed research programs was conducted by the Pennsylvania Transportation Institute for the Pennsylvania DOT and the Federal Highway Administration (FHWA) (13,14,15). In the PTI research, fifty-two full-scale arrestor bed tests were performed between 1984 and 1987. Testing was conducted in five arrestor beds; two which were constructed for the project and three which were operational. Each bed contained a different type of aggregate, one was crushed aggregate and the others were river run gravel. The test vehicles were a 10-wheel dump truck and an articulated tractor trailer. Entry speeds ranged from 29 to 60 mph and the test runs were conducted with the vehicles both empty and loaded.

In addition to the full-scale testing, laboratory testing of the aggregate was conducted in an attempt to correlate aggregate characteristics with vehicle deceleration. The tests performed were: gradation, specific gravity, L.A. abrasion, freeze-thaw, particle angularity, sphericity, and shearing resistance. The shearing resistance was conducted in a triaxial apparatus loaded both under dynamic and static conditions at confining pressures of 10, 20, and 30 psi.

Wang discusses a trend in compressive strength of the aggregate with loading rate (11). The compressive strength decreases to a minimum and then increases as loading rate increases. The decrease is attributed to kinetic friction being less than static friction, and the increase is attributed to the aggregates' inability to reorient when loaded extremely rapidly.

Wang concludes that all the river run aggregate perform similarly and the crushed aggregate is inferior for arrestor bed applications. Wang states: "In short, Pleasant Gap gravel is most uniform, PSU pea gravel is least angular, and Freeport gravel is most spherical. Thus, the nearly equal field performance of the three gravels should reflect more the combined effect of gradation, angularity, and sphericity than just the effect of inter particle friction and cohesion." One of the gravels that laboratory tests were performed on only had one full scale test and therefore no conclusions were drawn with respect to its performance.

The study resulted in two new models for predicting stopping distance in an arrestor bed: 1) a third order regression equation, and 2) a fully mechanistic model. The third order regression equation is given below:

$$L = AV + BV^2 + CV^3 \qquad (6)$$

Where:

L = Stopping Distance in feet

V = Vehicle Entry Velocity, mph

A,B,C = Constants Given in Table 1

TABLE 1 CONSTANTS FOR EQUATION 6

Constant	Percent Grade					
	-5	0	5	10	15	20
A	2.682	0.6	0.448	0.387	0.330	0.292
B	-0.119	0.0120	0.0149	0.0148	0.0143	0.0138
C	0.000661	0.00092	0.000314	0.000205	0.000153	0.000122

The PTI researchers assert that the third order regression equation is necessary to model the effects of "planing". Planing is described as the phenomenon whereby when a vehicle enters an arrestor bed at high speeds and the shear strength of the aggregates is such that the vehicle wheels will not penetrate the aggregates producing very little deceleration.

An energy-balance mechanistic model was developed. The sources of energy losses are as follows:

- momentum transfer - this is a transfer of the truck's momentum to the aggregate and is manifested by the movement of aggregate (generally spraying of aggregate from underneath the wheels)
- compaction resistance - the energy transferred from the truck to gravel by the action of compaction
- bulldozing resistance - the energy of the truck is dissipated by pushing a bow wave
- side shear resistance - the energy of the truck is dissipated through friction with the aggregates on the side of the tires.
- air drag, grade, and rolling resistance - these are the typical factors taken into account in vehicle drag models.

As can be seen from the brief description of the various losses there are many overlapping factors and it is difficult, if not impossible, to separate the effects. The mechanistic model is the most sophisticated attempt to date to model arrestor beds and takes into account vehicle characteristics as well as aggregate characteristics. However, some of the simplifying assumptions used for model development disagree with the results of the PTI experiments. For instance, although planing is significant enough to lead to a third order regression equation, the mechanistic model assumes the vehicle immediately penetrates to a depth that remains constant throughout the length of the run.

The ASU researchers conducted a sensitivity study of the mechanistic model and found that varying the input parameters for the aggregates over the range of values recommended by the PTI researchers produced only a 10% difference in the predicted stopping distance (16). Since experimental data produced by the PTI researchers and others demonstrated a greater sensitivity to aggregate characteristics, the PTI modeling approach was not evaluated further.

Arrestor Bed Pilot Testing

Baldwin documented a series of tests in selected loose gravel using a 4700 pound vehicle and entry speeds of 20 mph, 25 mph, and 30 mph (17). The testing was conducted to pilot test an arrestor bed that has a negative 4.6 percent grade for the first 800 feet and then transitions to a positive grade of

1.45 percent for the remainder. Baldwin had reviewed the Jehu literature and used equation (4) to calculate a required arrestor bed length of 2110 feet.

The bed was constructed 2480 feet long with a depth of 12 inches. The gravel specification was 100 percent passing the 1 inch sieve and 0 percent passing the number 4 sieve. Upon completion of the construction of the arrestor bed a plan was developed for monitoring performance. A typical example of the 15 recorded entries is a 69,000 pound vehicle entering at 85 mph, traveling 700 feet in the bed. Baldwin concluded the arrestor bed is probably three times as long as needed, but the added degree of safety is required due to the empirical nature of the design.

Allison et. al., have conducted research in New York on arrestor beds (18). Three full scale tests were conducted in a 528 foot long gravel arrestor bed with negative 10 percent grade and an array of sand-filled plastic drums used as an end treatment. The gravel depth is zero initially and increases to 24 inches in 50 feet. The aggregate was a rounded pea gravel with 100 percent passing the 1 inch sieve, approximately 98 percent passing the 0.5 inch sieve, and approximately 2 percent passing the number 4 sieve. The test vehicle was a 37,000 pound dump truck entering at 21, 41, and 56 mph. A radar gun was used to record the entry speed and two high-speed 16-mm movie cameras recorded the event. The film was analyzed to develop time-distance plots.

Allison et. al., report average deceleration of 0.18g, 0.4-0.6g, and 0.35 g for the 21, 41, and 56 mph entries respectively. They report that for a short time, between 0.5 and 1.0 seconds for each run, very little deceleration occurs.

Hardy et. al., documented testing by the Oregon Department of Transportation on negative 5.6 percent grade arrestor bed (19). The project was divided into three phases, aggregate selection, testing transverse mounds, and pilot testing the new arrestor bed.

Two aggregate gradations were tested: 1) aggregate passing the 3/4 inch sieve and retained on the 3/8 inch sieve, and 2) aggregate passing the 3/8 inch sieve and retained on the number 10 sieve. Hardy et. al., state that, "penetration tests showed the smaller gravel had slightly higher penetrability and therefore, slightly better rolling resistance." The effect of freezing was determined by wetting samples of the two aggregate gradations, allowing free draining, and freezing the samples. Once frozen, compression tests were conducted. The larger size aggregate exhibited a smaller compressive strength. An aggregate passing the 3/4 inch sieve and retained on the 1/2 inch sieve was used for the remainder of the project.

The on-site testing had several objectives, one of which was to determine if R varies with the load and velocity of the vehicle. Therefore, the testing included loaded and unloaded vehicles at each of three speeds, 25, 40, and 55 mph.

Thirty-eight entries were made with the longest travel distance of 484 feet when an empty 5-axle International entered the arrestor bed at 55 mph. Using rolling resistance values determined from the testing and extrapolating to 80 mph resulted in Table 2.

Hardy et. al., also report some in-service data. However, the report noted that in-service data was somewhat unreliable because it used driver's estimates of the entry speed. The longest entry recorded was by a tandem trailer estimated to be traveling at 85 mph. This vehicle penetrated the bed 1050 feet. Hardy et. al., also report several entries of more than 900 feet, one of which had an estimated entry speed of 100 mph.

TABLE 2 R TEST VALUES AND PREDICTED STOPPING DISTANCES FOR AN 80 MPH ENTRY SPEED

Vehicle	R	Required length
empty 2-axle	.25	1100
empty 5-axle	.24	1175
loaded 2-axle	.32	810
loaded 5-axle	.26	1040

Aggregate Freezing and Contamination

Derakhshandeh documents a 2-year study of aggregates in nine Colorado arrestor beds (2). Samples of aggregates were obtained from the bed to determine change in gradation and sources of contamination. Derakhshandeh states that there have been at least two incidents of trucks entering an ascending escape ramp and rolling back and jackknifing due to frozen aggregate.

The researchers concluded:

- Larger aggregates with low degrees of contamination only developed thin frozen crusts on the surface.
- Aggregate gradation changes from uniformly graded on the top of arrestor bed to well graded and contaminated at the bottom.
- Results failed to clearly show the increase in aggregate contamination or degradation with time.

Summary of Literature Review

The literature on arrestor beds provides much useful information of the performance of vehicles that enter a bed of granular material. One of the more significant findings in the literature is that vehicle weight has little if any influence on the stopping distance of a vehicle in the arrestor bed. In addition, several researchers reported that vehicle type did not affect the results in arrestor bed tests. This supports the decision by the ASU researchers to use a single vehicle type at one load condition.

There is a consensus in the literature that the media in the arrestor bed significantly affects stopping distance. However, there is no evidence in the literature that provides a means of reliably predicting a value of R based on tests of the aggregates. R values for aggregates in the literature range from 0.25 to 0.60. Thus, the value used by ADOT for design , 0.25, is conservative. The best direct evidence of the ability of an arrestor bed to perform as designed is to do pilot testing in the arrestor beds. This supports the decision to test several of the arrestor beds in the state.

ARIZONA ARRESTOR BEDS

At the time of the testing Arizona had six arrestor bed widely distributed throughout the state. Since the testing was conducted, a seventh arrestor bed has been constructed on SR 77 at milepost 154.3 in the south bound direction. All Arizona arrestor beds are shown in Figure 2.

Arizona arrestor beds have several common features including: asphalt concrete paved approach lanes, 12 foot wide asphalt concrete paved access lanes, concrete aprons with an embedded angle iron,

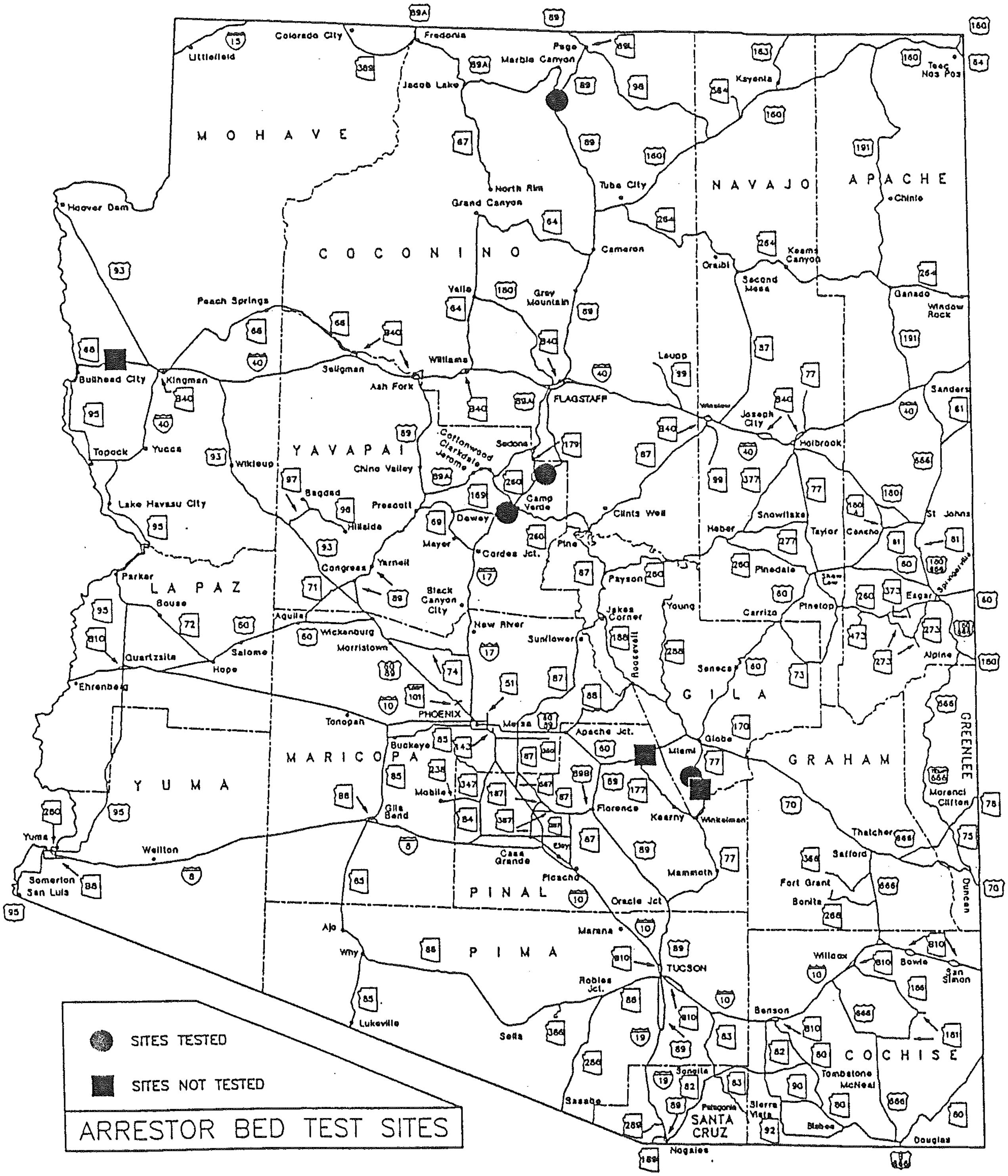


FIGURE 2 LOCATION OF ARIZONA ARRESTOR BEDS

cement treated base which the aggregate are placed on, and anchors set in concrete every 150 feet along the access lane for wreckers to use when they pull runaway vehicles out of the beds. The aggregate depth and grade vary from bed to bed. All beds have some transition from an initial aggregate depth to full aggregate depth.

There are two gravel specifications that have been used in Arizona arrestor beds, the original, Table 3, and the revised, Table 4. Only the arrestor bed on US 89 near Page currently has the originally specified aggregate. All other arrestor beds have the revised specification aggregate.

ADOT revised their specifications to provide a higher quality aggregate. The intention was to produce a more rounded, larger size aggregate, with less fines.

A summary of Arizona arrestor bed characteristics is given in Table 5. No information was available about the recently constructed bed on US 60.

TABLE 3 ADOT'S ORIGINAL ARRESTOR BED AGGREGATE SPECIFICATION

Sieve Size	% Passing
1/2"	100%
1/4"	10-70%
#8	0-20%
#16	0-4%
No Fractured Faces or	
Flakiness index	

TABLE 4 ADOT'S REVISED ARRESTOR BED AGGREGATE SPECIFICATION

Sieve Size	Percent Passing
1"	100%
1/2"	0-5%
#200	0-2%
Fractured Faces Limit	10% maximum
Flakiness index	7% maximum

TABLE 5 ARIZONA ARRESTOR BED SUMMARY

Location	Aggregate Specification	Depth / Transition*	Edge Condition	Bulk Sp. Gravity**	Angle of Repose**	Tested
I-17 NB	Revised	6" to 24" in 550'	west 4:1 slope, confined	2.64	34.0 degrees	Yes
I-17 SB	Revised	6" to 24" in 400' then at 900' increase to 36"	west 4:1 slope, east confined	2.59	34.0 degrees	Yes
US 89	Original	12" to 24" in 400'	4:1 slope both sides	2.55	31.6 degrees	Yes
SR 77	Revised	6" to 48" in 150'	confined both sides	2.60	33.5 degrees	Yes
US 60	Revised	***	***	***	***	No
US 68	Revised	6" to 48" in 150'	confined both sides	2.55	33.0 degrees	No

* As-Built information
** Tested by ASU
*** No information

I-17 NB

This arrestor bed is located on Interstate 17 at milepost 283 in the north bound direction just south of Camp Verde. An overview of the bed is shown in Figure 3. The bed was originally constructed in 1985 and at that time had pea gravel graded according to the original specification. In about 1987, during the construction of the I-17 SB bed, the aggregate was changed out for the revised specification. The aggregates are shown in Figure 4. The length of the bed is 1100 feet. The width of the bed is initially 40 feet wide and tapers to 26 feet in 400 feet. The east side of the bed has a 12 foot wide access road and the west side of the bed is left unconfined with aggregate sloping down at 4:1. The depth is initially 6 inches and transitions to 24 inches in 550 feet. The as-built plan indicates a 550 foot long vertical curve at the beginning of the bed as shown in Figure 5. Centerline grades were taken February 7, 1990 by ADOT surveyors and are shown in Figure 6. Superimposed onto the centerline grades are the approximated grades used with equation (1) to back-calculate the R for each run, negative 0.8 percent for 200 feet, 0 percent for 140 feet, and 1.2 percent for the remainder. The depth of gravel was not verified.

FIGURE 3 OVERVIEW OF I-17 NB ARRESTOR BED

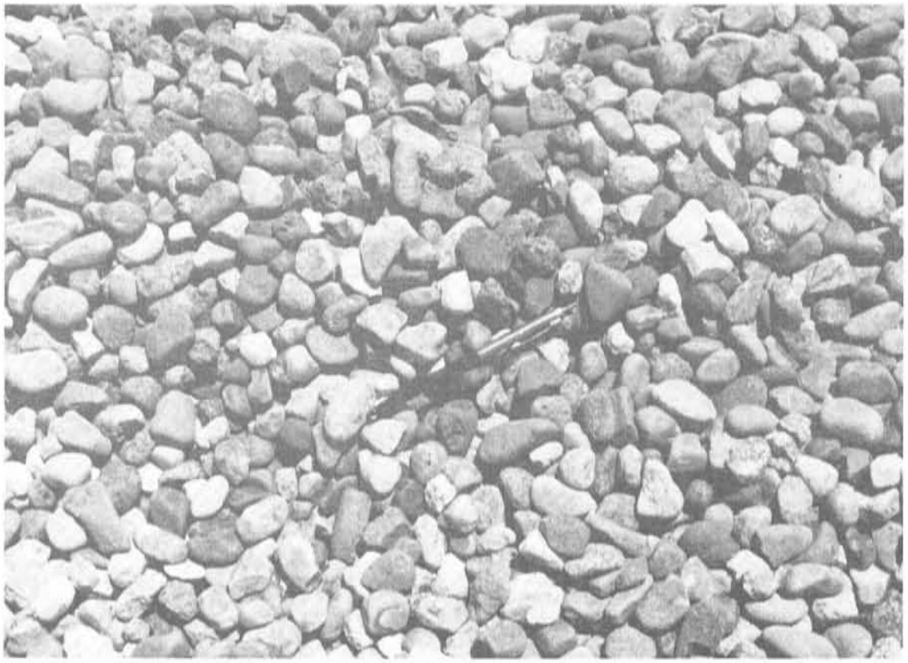
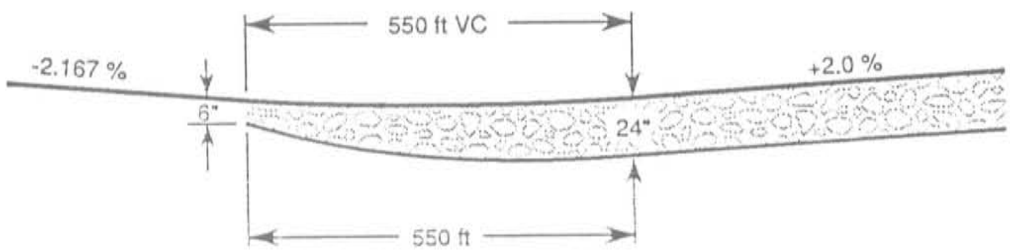


FIGURE 4 AGGREGATE IN I-17 NB ARRESTOR BED

FIGURE 5 I-17 NB AS-BUILT ARRESTOR BED GEOMETRY



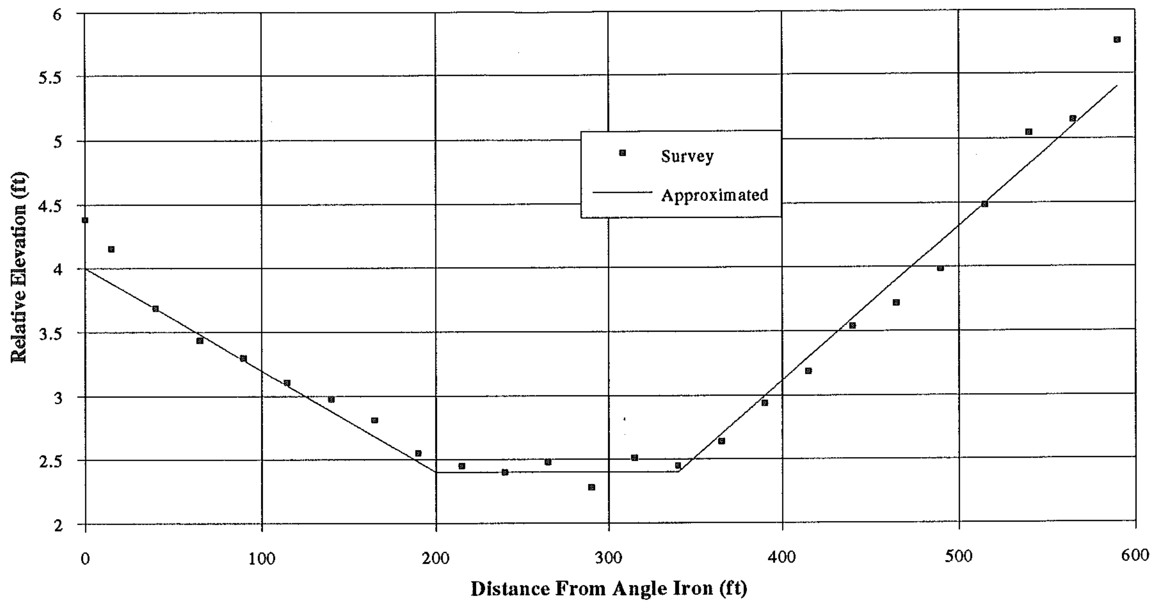


FIGURE 6 SURVEY PROFILE OF I-17 NB ARRESTOR BED

I-17 SB

This arrestor bed is located on Interstate 17 in the south bound direction at milepost 300 just north of Camp Verde. An overview of the bed is shown in Figure 7. The bed is initially 40 feet and tapers to 26 feet in 400 feet. The depth is initially 6 inches and transitions to 24 inches in 400 feet, then at 900 feet a 200 foot transition to 36 inches begins. The aggregates meet the revised specification. Figure 8 shows the nature of the aggregates. According to the as-built plans this bed has a 200 foot long vertical curve at the beginning of the bed as shown in Figure 9. The centerline longitudinal profile of the bed, as measured by ADOT surveyors on July 29, 1991, is given in Figure 10 along with the approximated grade for back-calculation of R, negative 4.7 percent for 150 feet and negative 1.7 percent for the remainder. The aggregate is confined on one east side by a 12 feet access road and left unconfined on the west side with a 4:1 slope. The length of this arrestor bed is 1884 feet.

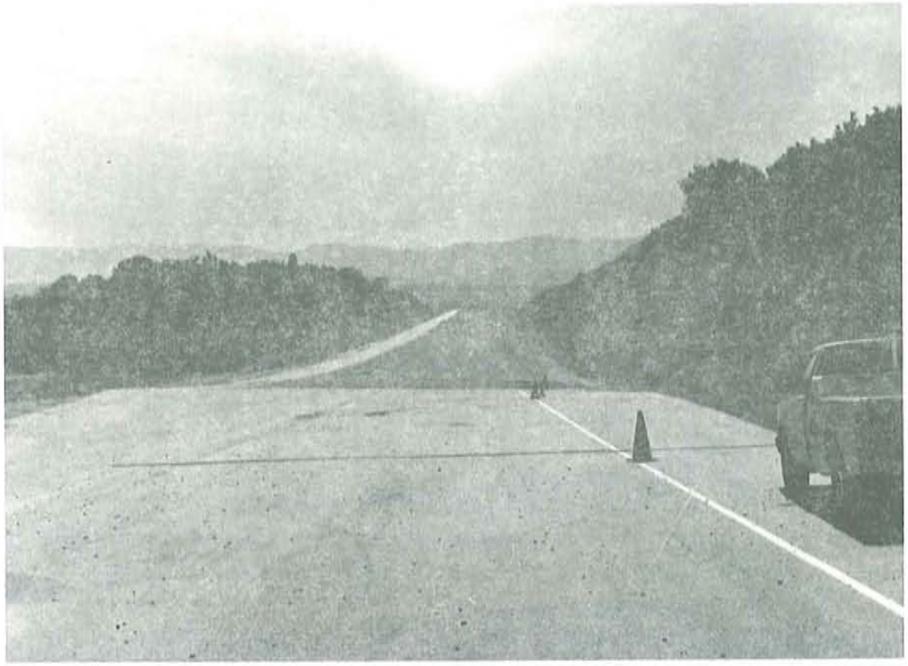


FIGURE 7 OVERVIEW OF I-17SB ARRESTOR BED

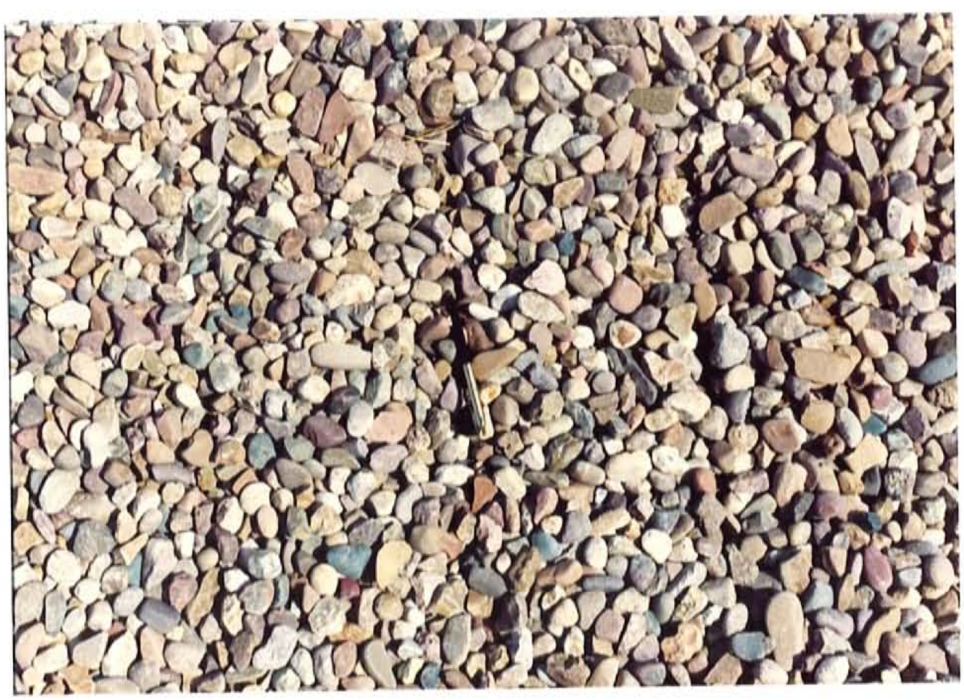


FIGURE 8 AGGREGATES IN I-17SB ARRESTOR BED

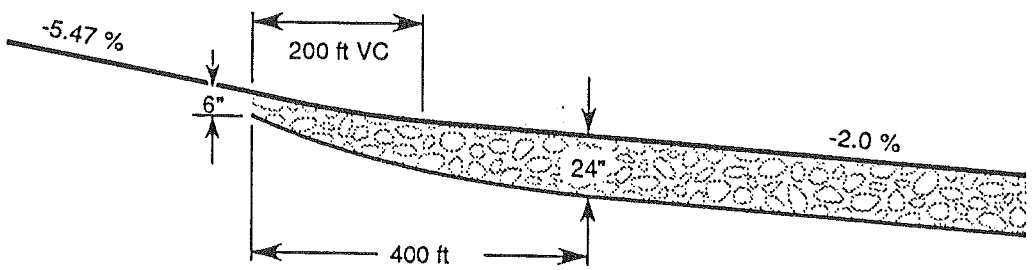


FIGURE 9 I-17 SB ARRESTOR BED AS-BUILT GEOMETRY

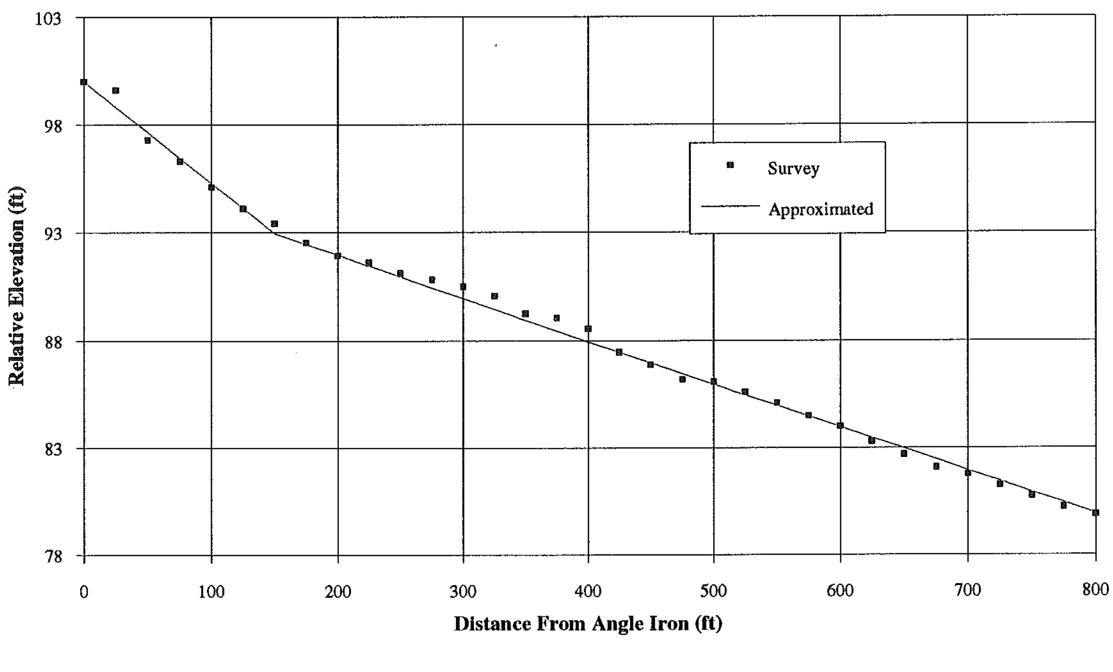


FIGURE 10 SURVEY PROFILE OF I-17 SB ARRESTOR BED

US 89

This arrestor bed, constructed in 1983, is located on US 89 at milepost 524.4 approximately 40 miles south of Page. An overview of the bed is shown in Figure 11. The bed is initially 40 feet wide and tapers to 26 feet. The length of this arrestor bed is 1240 feet. The bed is unconfined on both sides. The depth is initially 12 inches and transitions to 24 inches in 400 feet. The gravel in the bed meets the original specification. The nature of the aggregates is shown in Figure 12. Figure 13 shows the as-built geometry. Figure 14 gives the longitudinal profile at the centerline of the arrestor bed, as measured by ADOT surveyors on March 28, 1990, along with the approximated grades for back-calculation of R, negative 3 percent for 150 feet and negative 2 percent thereafter.

FIGURE 11 OVERVIEW OF US 89 ARRESTOR BED

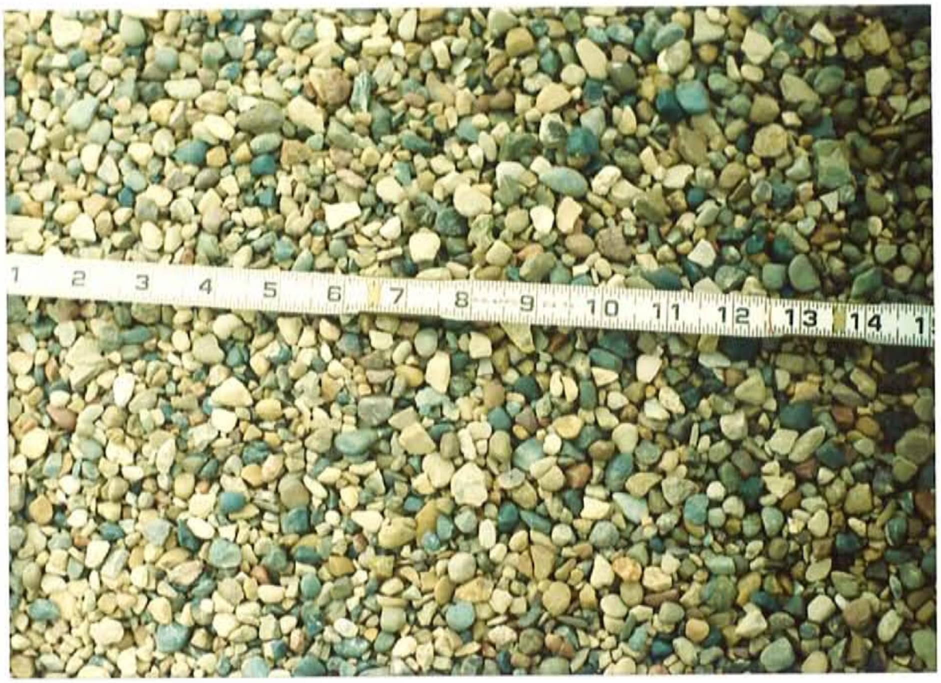


FIGURE 12 AGGREGATE IN US 89 ARRESTOR BED

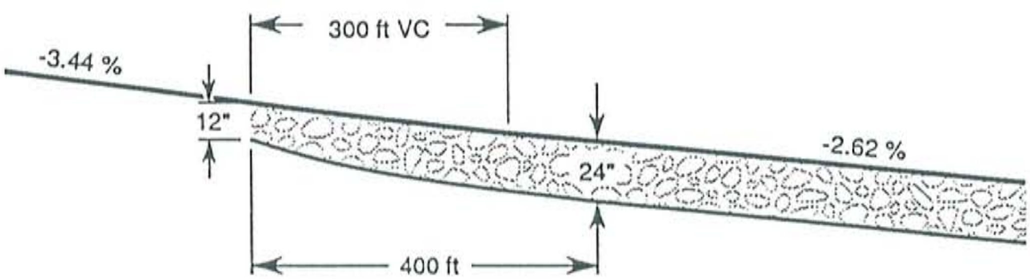


FIGURE 13 US 89 ARRESTOR BED AS-BUILT GEOMETRY

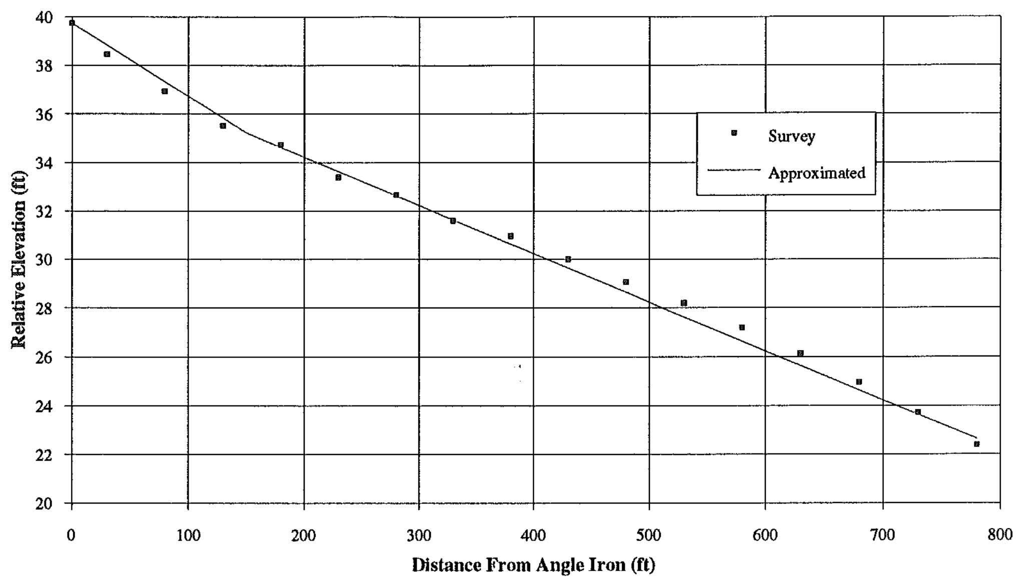


FIGURE 14 SURVEY PROFILE OF US 89 ARRESTOR BED

SR 77

This arrestor bed is located on State Route 77 at milepost 155.7 between Globe and Winkleman. This bed is 40 feet wide for the entire 1,000 foot length. An overview of the bed is shown in Figure 15. The aggregate in the bed meets the revised specification. The nature of the aggregate is shown in Figure 16. The as-built plan indicates that there is a 600 foot long vertical curve at the beginning of the bed as shown in Figure 17. Figure 18 gives the longitudinal profile at the centerline of the arrestor bed, as measured by ADOT surveyors on July 31, 1991, along with the approximated grades for back-calculation of R, negative 2.3 percent for 120 feet, 0 percent for 100 feet, and 2.1 percent for the remainder. This bed is confined by an access road on the east side and by a concrete aggregate retainer on the west side. The initial depth of gravel is 12 inches and transitions to 48 inches in 150 feet.

FIGURE 15 OVERVIEW OF SR 77 ARRESTOR BED

FIGURE 16 AGGREGATE IN SR 77 ARRESTOR BED

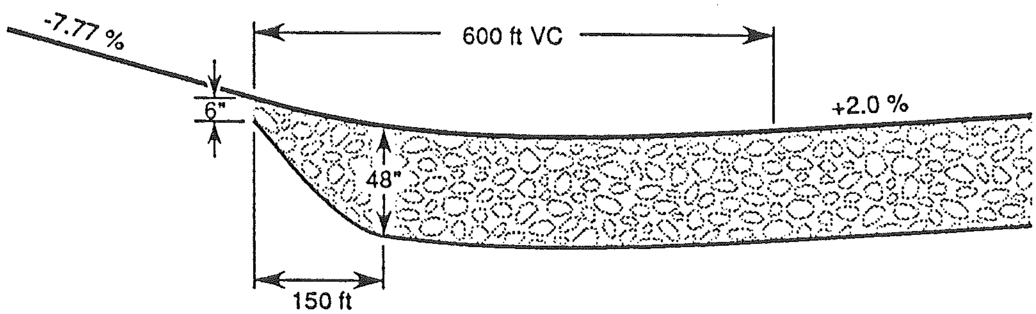


FIGURE 17 SR 77 ARRESTOR BED AS-BUILT GEOMETRY

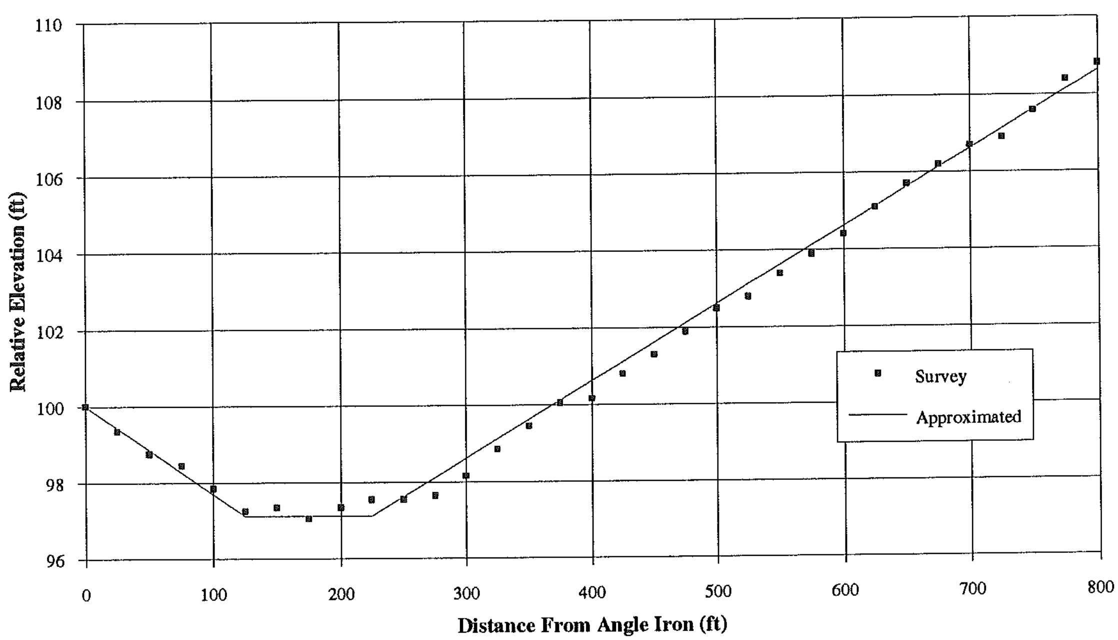


FIGURE 18 SURVEY PROFILE OF SR 77 ARRESTOR BED

Comparison of the Four Arrestor Bed Characteristics

Details of the four arrestor beds that were used in the testing program have been given. All the beds have a vertical curve that transitions the grade of the paved approach lane to the final arrestor bed grade. In two the beds, I-17 NB and SR 77, the final grade is positive and in the other two beds, I-17 SB and US 89, the final grade is negative. Grades have been approximated in order to back-calculate R using equation (1). Three beds have the same aggregate specification, I-17 NB, I-17 SB, and SR 77, while US 89 has the smaller pea gravel. The shortest arrestor bed is 1,000 feet while the longest is 1884 feet. Each bed has a different average depth and length of transition to full depth.

TESTING

Testing was administered by the ASU research team. Bed preparation was performed by ADOT maintenance workers from the area in which the tests were conducted. The maintenance workers who smoothed the arrestor beds between runs were not necessarily responsible for the normal maintenance of the beds. In several cases, the equipment operators were inexperienced and had difficulty smoothing the beds.

Initial arrestor bed testing consisting of twelve runs was conducted in December, 1989. The treatments for this testing were two levels of speed - 45 mph and 65 mph, and three levels of tracking - smooth, tracked, and double tracked. There was also a run of 45 mph into the tracks left by a 65 mph run. The only type of bed preparation equipment used for the December 1989 testing was a bulldozer. A comparison of the December 1989 data with the PTI regression model indicated a lack of agreement. This prompted ADOT to contract the services of a statistical consultant, Dr. Mary Anderson of the Industrial Engineering Department at ASU, to develop an experimental plan to perform tests in as many of the other arrestor beds in Arizona as possible. The experimental test plan is shown in Appendix A.

Experimental Test Plan

The basis of the experimental plan was to conduct a 2x2x3 replicated experiment in as many of Arizona's arrestor beds as possible. The experimental treatments were as follows: 1) two levels of speed;

45 mph and 65 mph, 2) two levels of tracking, and 3) three levels of equipment type; bulldozer, front-loader, and rake.

The December 1989 tests used only the bulldozer for bed preparation. There was however two variations of the tracked condition: 1) one entry into the tracks left after two entries - "double tracking", and 2) a tracked entry at 45 mph when the original entry had been at 65 mph.

Design A of the experimental plan had two purposes: first; to confirm the double tracked entries made in the December 1989 experiment, and second; to provide a portion of the data needed for a full factorial in the I-17 northbound arrestor bed. The test plan also contained a tracked run at 65 mph following a smooth run at 45.

The intent of the experimental plan was to perform Design A in I-17 NB and determine if the data from the December 1989 testing was from the same statistical distribution as the runs from 1991. If the data was determined to be from the same statistical distribution then design A1 would be performed to add the equipment treatment and form the 2x2x3 factorial. If the December 1989 data did not come from the same statistical distribution as the 1991 data, then the December 1989 data would be discarded and Design A2 would be performed. The difference between Design A1 and A2 was only six runs. Therefore, ADOT and ASU agreed to perform the larger experiment to avoid the possibility of having double mobilization costs.

Data Collection Equipment

At the start of the project, equipment was sought that could measure the deceleration of vehicles in arrestor beds. The equipment needed to operate remotely so that the deceleration of runaway trucks in the arrestor beds could be observed. Equipment used by other researchers did not have these capabilities. Thus, the ASU research team designed equipment that met the needs of this research project. The details of the equipment development, reasons for the selection of the various components, and the software required to run the system were documented by Myers (6). The following discussion is limited to an overview of the equipment and its operation.

The equipment used a stationary radar unit to measure the velocity of the vehicle. The data acquisition and control unit recorded the velocity every 1/20 of a second after the vehicle entered the arrestor bed. The components of the system are:

1. Kustom Electronics stationary radar unit (model "Road Runner") - Output from the unit is a nearly continuous measure of Doppler frequency with 72.023 hz. equal to one mile per hour. The unit detects speeds from 12 to 199 mph up to a range of 2000 feet under ideal conditions. In order to obtain the most reliable data, the ASU research team worked with the manufacturer to increase the sensitivity of the radar unit down to 5 mph.

2. Hewlett-Packard data acquisition and control unit (model HP48060) - The programmable features of this unit permitted remote operation. Manufacturer specifications indicated that the unit met project needs for allowable operating conditions, speed of data acquisition, memory ability, and power requirements. The ASU research team developed computer code for the HP48060 that is documented in Myers (6).

3. Signal conditioner - frequency to voltage (custom electronics developed by the ASU researchers) - The radar unit generates a frequency that is proportional to measured speed. This frequency signal was converted to a voltage signal that could be interpreted by the analog to digital converter in the HP48060. The output of the converter had a linear scale with zero volts corresponding to zero mph and one volt equal to 199 mph. The schematic for the frequency to voltage converter is presented in Myers (6).

4. Vehicle detection switches - These units contain two copper strips separated by a collapsible medium. A vehicle tire crossing over the switch collapses the separating medium allowing contact of the copper switches. These units worked well for the controlled testing but were a maintenance problem for remote operation.

5. Pulse extender (custom electronics developed by the ASU research team) - The duration of the signal from the tape switches was too short to ensure that the data recorder would

capture the signal. A simple circuit was developed to extend the duration of the tape switch signal to exceed the cycle time of the data logger. This ensures that the data logger captures the signal from the tape switches. The schematic for the pulse extender is presented by Myers (6).

6. Power Supply - Two deep cycle 6 volt 220 amp-hour batteries, connected in parallel, provided the power required for the radar and data logger. A 30 watt phovolatic panel was used to keep the batteries charged for remote operation.

7. Equipment cabinet - Items 1, 2, 3, 5, and 6 were mounted in an aluminum cabinet as shown in Figure 19.

The components of the equipment are connected as shown in Figure 20 and a typical arrestor bed installation is shown in Figure 21. For remote operation, the first tape switch at the entrance to the escape ramp causes the data recorder and the radar unit to power up and prepare for data collection. The second tape switch begins the data collection process. For manual operation, only the second tape switch is required as the operator powers up the unit at the start of a test run.

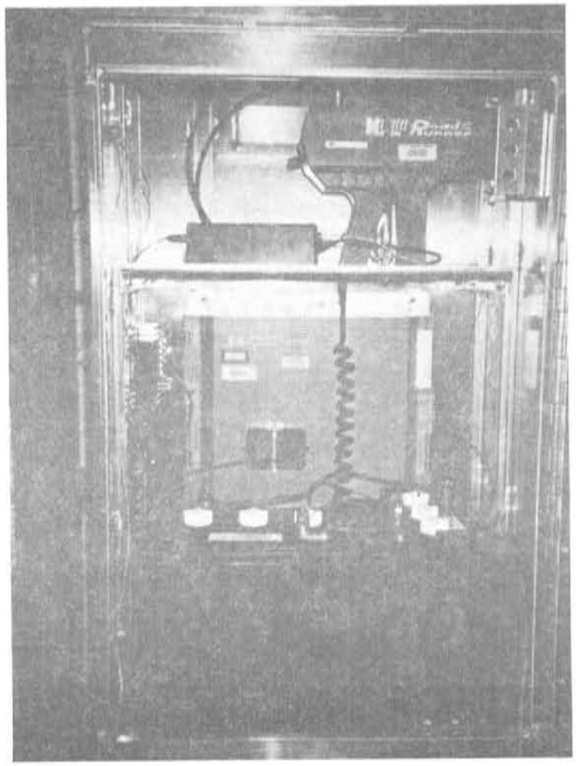


FIGURE 19 VIEW OF THE DATA COLLECTION INSIDE THE CABINET

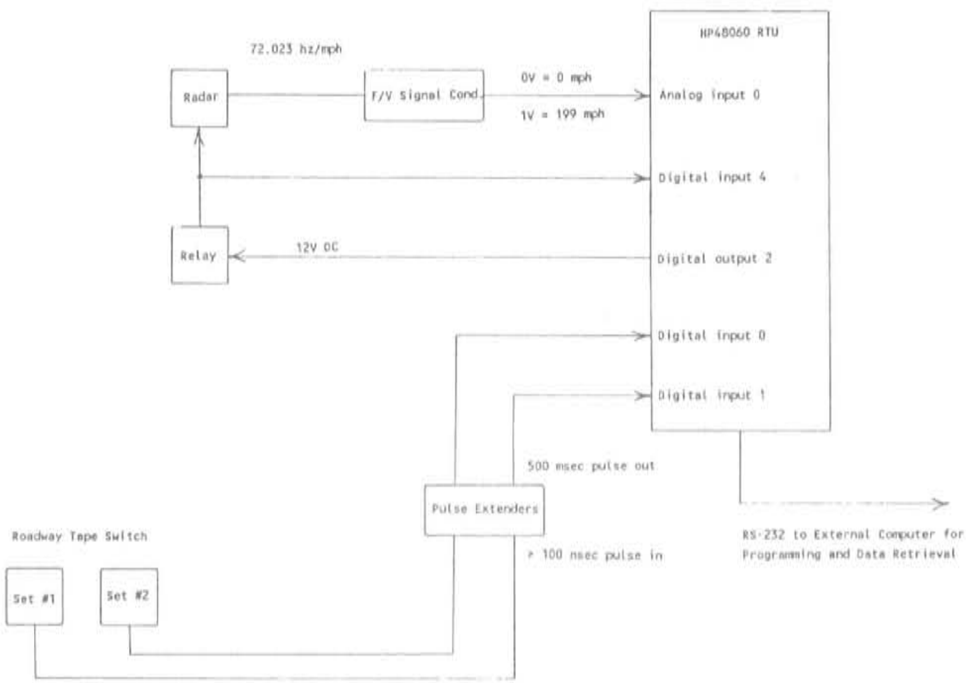


FIGURE 20 BLOCK DIAGRAM OF THE EQUIPMENT CONNECTIONS

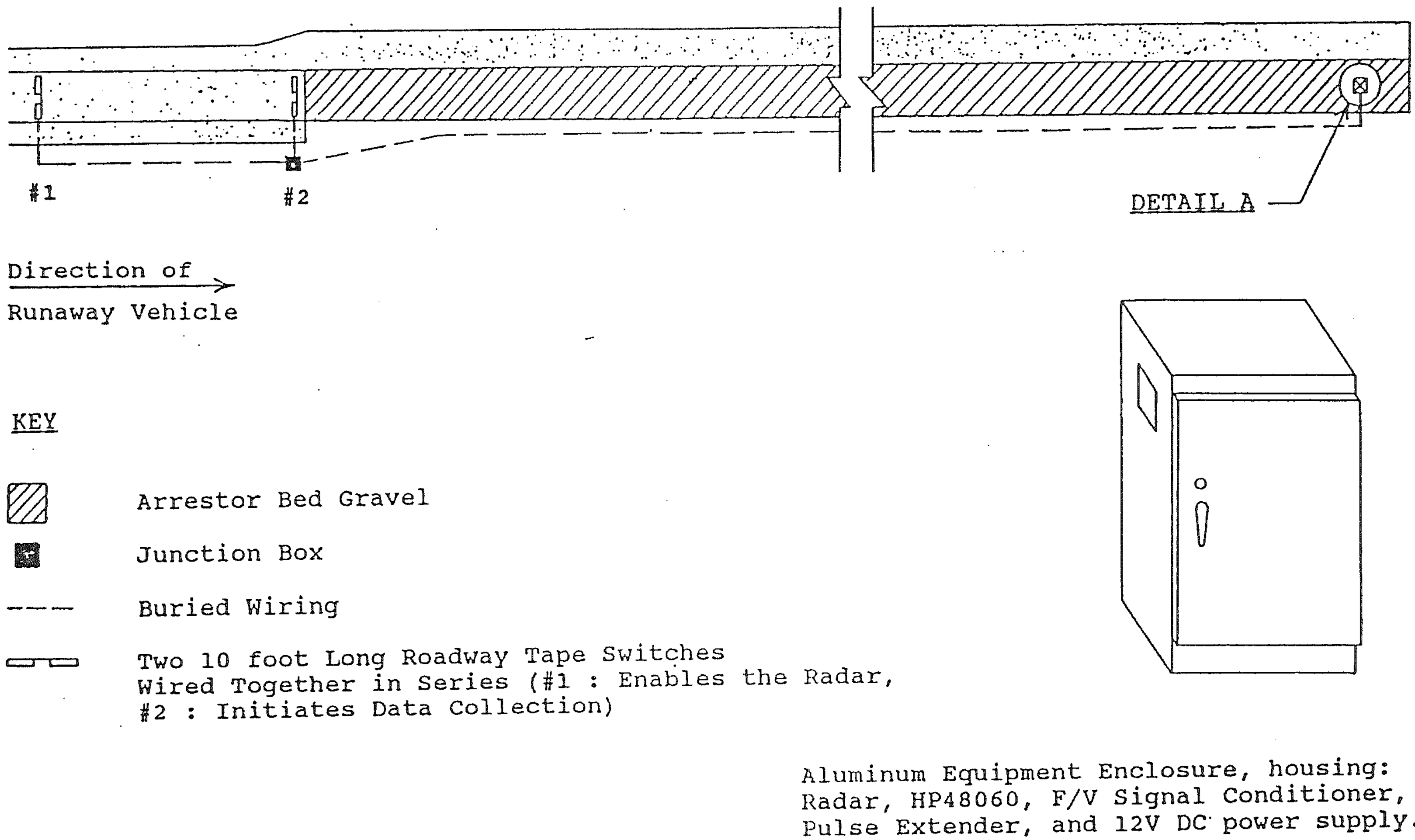


FIGURE 21 TYPICAL FIELD INSTALLATION OF THE DATA COLLECTION EQUIPMENT

The system is programmed to collect 240 speed-time data pairs, one every 1/20th of a second, and then power down until the first tape switch is activated again. During the initial tests of the system, it was determined that the cycle time of the computer varied slightly. Thus, the actual time of each speed measurement was recorded from the clock in the data recorder. Figure 22 shows a typical time vs. velocity curve with all 240 data pairs obtained from the data acquisition unit. The large spike in Figure 22 occurs when the speed of the truck drops below the sensitivity of the radar unit. Once this happens, the unit senses traffic on the highway adjacent to the arrestor bed. Subsequent time vs. velocity charts in this report have these spikes edited out. The program in the data logger could have been modified to turn off the data collection once the truck speed was below the sensitivity of the radar unit. However, programming a constant data collection time was simpler and allowed the data collection unit to cycle more rapidly.

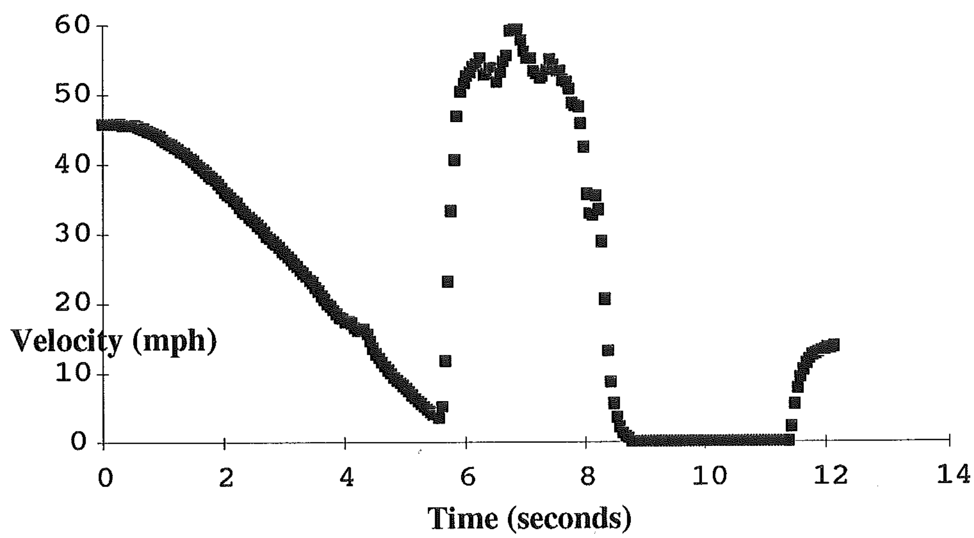


FIGURE 22 TYPICAL TIME VS. VELOCITY CURVE

In addition to the automatic equipment, the length of each run during the experiment was measured with a manual odometer.

Bed Preparation Equipment

Three types of bed preparation were used in the testing: 1) bulldozer (Caterpillar D6 or comparable), 2) front-end loader (Case W20C or comparable), and 3) rake. The rake was fabricated by ADOT maintenance forces responsible for maintaining the bed at US 89. The rake was constructed from a U-channel with 8 inch pieces of rebar welded to one flange at approximately 12 inch on center. The rake was attached to a bulldozer as shown in Figure 23.

FIGURE 23 RAKE USED FOR ARRESTOR BED MAINTENANCE

Data Reduction

To back-calculate the R value for each run the approximated grades given in Figures 6, 10, 14, and 18 were used to determine an average grade for each run based on the stopping distance. The average grade was used in equation (1) along with the actual entry velocity as measured by the radar to determine the R value. For example, the stopping distance for run number 10, I-17 NB (1991), was 378 feet. Therefore, the average grade of -0.0028, was computed as shown below, and the actual entry velocity of 65.3 mph were used in equation (1) to determine R.

$$G_{ave} = \frac{-.008*200+0*140+.014*38}{378} = -0.0028$$

Testing Details

The experiments were run in the following order: 1) I-17 NB **December 1989**, 2) I-17 NB **Design A**, 3) I-17 NB **Design A2**, 4) I-17 SB **Design A3**, 5) US 89 **Design A3**, and 6) SR 77 **Design A**. All 1991 testing was conducted in June.

Due to the time lag between the two sets of tests, it was not possible to use the same truck for both sets of data collection. However the trucks were similar; both were articulated 3 axle tractors with a 2 axle unloaded flatbed semi-trailers. The December 1989 vehicle weighed 33,000 pounds and the 1991 vehicle weighed 31,000 pounds. The December 1989 vehicle is shown in Figure 24 and the vehicle for all other testing is shown in Figure 25.

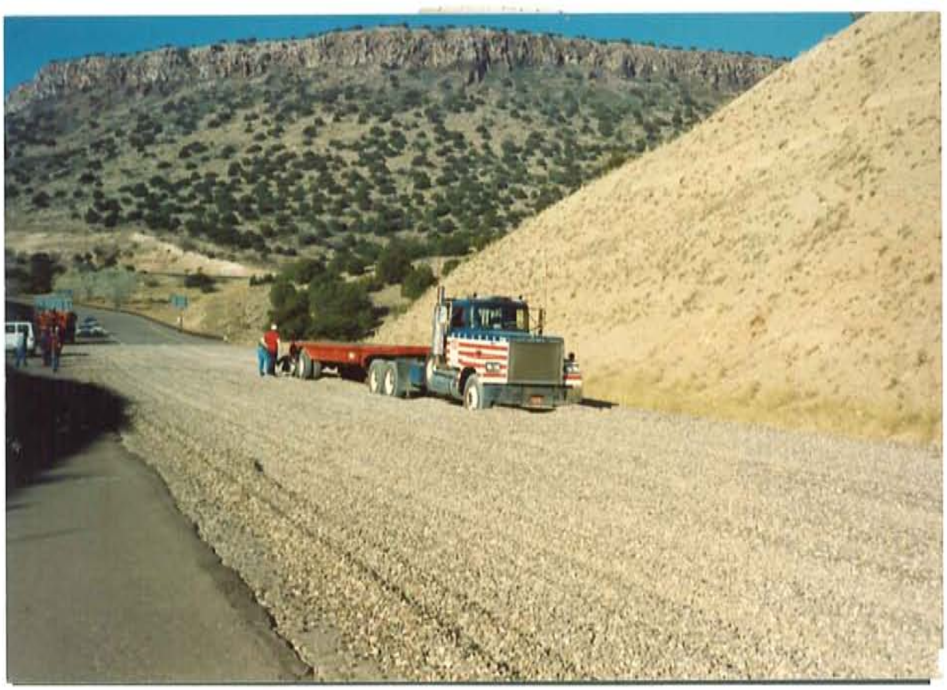


FIGURE 24 TEST VEHICLE USED IN DECEMBER 1989 TESTING

FIGURE 25 TEST VEHICLE USED FOR ALL 1991 TESTING

Different drivers were used for the December 1989 and June 1991 testing. The driver for the 1991 testing is part owner of a wrecking service that does the majority of the towing from the two most frequently used arrestor beds in Arizona, I-17 NB and I-17 SB. This driver does most of the towing of vehicles from these two arrestors and his comments were noted where appropriate.

For all runs the driver accelerated to the design entry speed then disengaged the drive-train just before entering the gravel. After each run the driver and his assistant used their towing rig to extract the truck from the gravel. Sometimes the test vehicle could be pulled straight back and other times the towing rig had to be setup on the 12 foot access road. When the tow rig was setup on the access road the wheel ruts were disturbed by the sideways pulling of the test vehicle.

I-17 NB Observations and Results

The testing in this bed took place at two times: 1) preliminary testing in December, 1989, and 2) in the first week of June, 1991. The December 1989 testing consisted of 12 runs. Of the 12 runs, only 8 were suitable to include in the statistical analysis. In runs number 5 and 6 a mound was left unintentionally by the equipment operator that caused large vertical oscillations of the truck which prompted the driver to use his brakes. Runs number 9 and 10 were made under treatments that were not considered in the statistical analysis. All runs in the December 1989 testing were made in the middle of the bed and all bed preparation was with a Caterpillar D-6 bulldozer, hereafter referred to as Dozer.

Testing began on June 2, 1991. Because this bed receives a large number of entries during the summer months a decision was made to perform runs on either side of the bed. This left the other side open for an emergency entry.

Four runs were made the first day, all consisting of Dozer preparation. The loader arrived in the middle of the second day and the Rake arrived late the second day. For runs 1 through 8, the 45 mph entries were made in the west side of the bed and all 65 mph runs were made in the east side. After the eighth run there was more dispersion between the of 45 mph runs and 65 mph runs between sides of the bed.

The equipment operator that performed the bed smoothing and fluffing for the I-17 NB, June 1991 testing was experienced and made the bed appear smooth. The equipment operator worked the material by back-dragging away from the front of the bed to make it smooth and then he lowered his rippers into the aggregate and scarified the bed in three or four passes. In some instances, he used his front blade to push aggregate from about 20-30 feet from the concrete apron into the area about 5 feet form the concrete apron thereby filling a depression. However, he did not transport material from the back of the bed to the front portion in order to replace the aggregate that had been sprayed from the bed. The operator mentioned that he could see a difference in the runs when he placed his rippers deeper in the bed.

The rake did not work well for the testing in this bed. The equipment operator and his assistant had never used the rake before and had problems attaching it to the Dozer. Once the rake was chained to the back of the Dozer, it was discovered that the rake did not have sufficient weight to penetrate the aggregate. The maximum observed penetration of the rake teeth into the aggregate was 2 inches.

The results of the testing at I-17 NB are given in Tables 6 through 8.

The minimum stopping distance for all the I-17 NB testing was 198 feet, while the maximum was 573 feet. The minimum R value was 0.24, and the maximum was 0.41. The maximum R value occurred during a run in which a depression was left in the bed by the Dozer, causing the driver to use brakes.

TABLE 6 RESULTS I-17 NB (DECEMBER 1989)

Bed Prepar ation	Design Entry Speed (mph)	Run order	Measured Entry Speed (mph)	Distance Traveled (ft)	R
1. Dozer	45	1	44.6	201	.34
2. Tracked	45	2	44.0	263	.25
3. Dozer	65	3	65.5	405	.35
4. Tracked	65	4	no record	491	.28
5. Dozer*	65	5	66.7	362	.41
6. Tracked*	65	6	67.1	386	.39
7. Dozer	65	7	65.5	430	.33
8. Dozer	65	8	65.5	411	.35
9. Tracked*	45	9	no record	253	.27
10. Tracked*	45	10	45.0	260	.26
11. Smooth	45	11	44.2	198	.33
12. Tracked	45	12	44.4	242	.28

*runs that were not included in the statistical analysis

TABLE 7 RESULTS I-17 NB (DESIGN A)

Bed Preparation	Design Entry Speed (mph)	Run Order	Measured Entry Speed (mph)	Distance Traveled (ft)	Date	Location	R
1. Dozer	45	1	45.8	204	6/3/91	West	.35
2. Tracked	45	2	missed	266	6/3/91	West	.26
3. Tracked*	45	3	47.4	278	6/3/91	West	.27
4. Dozer	65	5	61.8	395	6/4/91	East	.32
5. Tracked	65	6	64.1	485	6/4/91	East	.28
6. Tracked*	65	7	66.5	516	6/4/91	East	.28
7. Tracked	65	not done					
8. Dozer	65	10	65.3	378	6/4/91	West	.38
9. Tracked	65	12	66.1	464	6/4/91	West	.31
10. Dozer	65	11	64.9	425	6/4/91	East	.33
11. Tracked	65	13	missed	491	6/4/91	East	.28
12. Dozer	45	8	47.4	224	6/4/91	West	.34
13. Tracked*	65	9	65.7	414	6/4/91	West	.35
Dozer**	65	4	56.4	325	6/3/91	East	.33

*Runs not included in statistical analysis

**This was the first 65 mph run in the 1991 testing and driver did not achieve 65 mph. The data point is not numbered because it was not included in the experimental design.

TABLE 8 RESULTS I-17 NB (DESIGN A2)

Bed Preparation	Design Entry Speed (mph)	Run Order	Measured Entry Speed (mph)	Distance Traveled (ft)	Date	Location	R
1. Rake	65	14	65.1	548	6/4/91	East	.25
2. Tracked	65	16	64.3	545	6/4/91	East	.25
3. Loader	45	26	46	228	6/5/91	West	.31
4. Tracked	45	27	45.8	281	6/5/91	West	.25
5. Rake	45	18	46.4	250	6/5/91	West	.29
6. Tracked	45	19	46.4	292	6/5/91	West	.25
7. Loader	65	22	65.4	488	6/5/91	East	.29
8. Tracked	65	23	65.74	573	6/5/91	East	.25
9. Dozer	45	30	45.2	208	6/5/91	Middle	.33
10. Tracked	45	31	45.6	269	6/5/91	Middle	.26
11. Loader	65	24	65.9	492	6/5/91	West	.29
12. Tracked	65	25	63.9	521	6/5/91	West	.26
13. Rake	45	20	46.8	278	6/5/91	East	.27
14. Tracked	45	21	45.6	329	6/5/91	East	.21
15. Loader	45	28	45.4	237	6/5/91	East	.29
16. Tracked	45	29	45.6	292	6/5/91	East	.24
17. Rake	65	15	65.1	489	6/4/91	West	.29
18. Tracked	65	17	65.7	546	6/4/91	West	.26

I-17 SB Observations and Results

Testing in the I-17 SB bed took place the second week in June, 1991. Side runs were made in this bed for the same reason they were in the I-17 NB arrestor bed. Upon first arriving at the site it was noticed that the cement treated base was exposed about 10 feet past the concrete apron. Apparently there had been several entries in the bed since the last maintenance was performed. The first test scheduled was a 45 mph, smooth, Dozer preparation. The bed was prepared to accommodate an entry of up to 250 feet. The first entry produced a stopping distance of 318 feet.

The arrestor bed appeared to have a concave shape that extended from side to side and about 40 to 50 feet from the concrete apron. The bed appeared to become continually thinner with each test run. The driver commented that this bed did not have nearly the stopping power of the I-17 NB bed.

Three maintenance workers operated the bed smoothing equipment. They had some difficulty and it appeared they were less experienced than the equipment operator at I-17 NB. The maintenance workers commented that the front-end loader was digging into the gravel making it hard to smooth the bed.

The maintenance workers made a maximum effort to use the rake. In some instances two workers stood on the rake while the third operated the dozer. In other instances they used chains to fix large boulders, approximately 2 feet in diameter, on top of the rake. Still the rake did not penetrate the aggregate.

The results of the testing at I-17 SB are given in Table 9.

TABLE 9 RESULTS I-17 SB (DESIGN A3)

Bed Preparation	Design Entry Speed (mph)	Run Order	Measured Entry Speed (mph)	Distance Traveled (ft)	Date	Location	R
1. Dozer	45	1	46.2	318	6/10/91	East	.25
2. Tracked	45	2	46.4	364	6/10/91	East	.22
3. Rake	65	17	65.9	522	6/11/91	East	.30
4. Tracked	65	18	65.9	602	6/11/91	East	.26
5. Loader	45	9	45.6	319	6/10/91	Middle	.24
6. Tracked	45	10	45	382	6/10/91	Middle	.20
7. Dozer	65	5	65.7	507	6/10/91	Middle	.30
8. Tracked	65	6	65.5	541	6/10/91	Middle	.28
9. Rake	45	21	45	272	6/11/91	West	.27
10. Tracked	45	24	46.8	335	6/11/91	West	.24
11. Loader	65	13	65.9	509	6/11/91	East	.30
12. Tracked	65	14	missed	599	6/11/91	East	.25
13. Dozer	45	3	45.8	300	6/10/91	West	.26
14. Tracked	45	4	46.4	343	6/10/91	West	.23
15. Loader	65	15	65.9	525	6/11/91	East	.30
16. Tracked	65	16	65.7	600	6/11/91	East	.26
17. Rake	45	22	46.6	342	6/11/91	Middle	.23
18. Tracked	45	23	46	426	6/11/91	Middle	.19
19. Loader	45	11	46.6	275	6/11/91	West	.29
20. Tracked	45	12	48.8	344	6/11/91	West	.25
21. Dozer	65	7	65.5	486	6/10/91	Middle	.31
22. Tracked	65	not done	(safety)				
23. Rake	65	19	missed	533	6/11/91	Middle	.28
24. Tracked	65	20	65.5	622	6/11/91	Middle	.25

TABLE 10 RESULTS US 89 (DESIGN A3)

Bed Preparation	Design Entry Speed (mph)	Run Order	Measured Entry Speed (mph)	Distance Traveled (ft)	Date	R
1. Dozer	45	1	50.2	300	6/18/91	.30
2. Tracked	45	2	44.6	304	6/18/91	.24
3. Rake	65	3	64.7	501	6/18/91	.30
4. Tracked	65	4	64.5	571	6/18/91	.27
5. Loader	45	5	47.4	249	6/18/91	.32
6. Tracked	45	6	44.6	275	6/18/91	.26
7. Dozer	65	7	64.5	518	6/18/91	.29
8. Tracked	65	8	62.5	560	6/18/91	.26
9. Rake	45	9	45	255	6/18/91	.29
10. Tracked	45	10	45.6	289	6/18/91	.26
11. Loader	65	11	63.9	512	6/18/91	.29
12. Tracked	65	12	64.1	538	6/18/91	.28
13. Dozer	45	16	45.2	259	6/19/91	.29
14. Tracked	45	17	45.4	306	6/19/91	.25
15. Loader	65	18	64.7	513	6/19/91	.29
16. Tracked	65	19	65.1	566	6/19/91	.27
17. Rake	45	13	45.6	251	6/19/91	.30
18. Tracked	45	14	no record	303	6/19/91	.25
19. Loader	45	20	45.4	260	6/19/91	.29
20. Tracked	45	21	45.4	310	6/19/91	.24
21. Dozer	65	22	63	480	6/19/91	.30
22. Tracked	65	23	63.9	556	6/19/91	.27
23. Rake	65	24	63.2	460	6/19/91	.31
24. Tracked	65	25	64.5	544	6/19/91	.28
Rake Double Track*	45	15	45.0	318	6/19/91	.23
Rake*	Max	26	70.7	579	6/19/91	.31

*Runs not included in the statistical analysis

The minimum stopping distance in the I-17 SB bed was 272 feet, and the maximum 622 feet. The minimum R value was 0.19 and the maximum R value was 0.31.

US 89 Observations and Results

The results of the testing at US 89 are given in Table 10. The maintenance crew appeared well experienced and able to remove the majority of roughness in the bed with the given equipment. However, the Dozer at this bed did not have rippers. Therefore there was no scarifying during the Dozer prepared runs. The maintenance workers at this bed were experienced at using the rake and were able to stand on it and attain the full penetration of 6 inches. The ability to successfully use the rake on this arrestor bed was probably due to the fact that it was the only bed with the original specification aggregate.

The driver of the test vehicle indicated that the pea gravel gave a smoother ride than the other arrestor beds. The pea gravel did not seem to spray from the bed as much as the larger aggregate tested in I-17 NB and I-17 SB.

The minimum stopping distance in the US 89 bed was 249 feet, and the maximum was 579 feet. The minimum R value was 0.24 and the maximum was 0.32. The maximum stopping distance occurred during an unplanned run in which the driver tried to achieve a maximum entry velocity.

SR 77 Observations and Results

The results of the testing at SR 77 are given in Table 11. Testing in this bed took place during the fourth week in June, 1991. Two unscheduled runs were made in the bed at the beginning of the day, a 45 mph smooth and a 45 mph tracked. No bed preparation was used before these two unscheduled runs and they were intended to simulate the conditions that a real runaway truck would experience.

One maintenance worker was available to operate the Dozer in this bed. He expressed concern that it had been quite some time since he had operated a bulldozer. It required approximately 1.5 hours to smooth the bed after the third run. The bed still did not seem as smooth as desired after this extended time period.

The driver expressed apprehension about the runs in this bed. The bed produced the shortest

TABLE 11 RESULTS SR 77 (DESIGN A)

Bed Preparation	Design Entry Speed (mph)	Run Order	Measured Entry Speed (mph)	Distance Traveled (ft)	Date	R
1. Dozer	45	3	45.6	200	6/28/91	.36
2. Tracked	45	4	46.8	248	6/28/91	.30
3. Dozer	65	5	66.3	369	6/28/91	.40
4. Tracked	65	6	64.9	395	6/28/91	.35
5. Dozer	65	7	64.7	344	6/28/91	.41
6. Tracked	65	8	65.3	381	6/28/91	.37
7. Dozer	45	9	46.2	203	6/28/91	.36
8. Tracked	45	10	45.2	241	6/28/91	.29
Unprepared*	45	1	45.6	230	6/28/91	.31
Tracked*	45	2	44.8	225	6/28/91	.31

* Runs not included in the analysis

stopping distances and the driver undoubtedly experienced larger deceleration forces. In addition the roughness of the bed due to the bed preparation may have added to his apprehension.

The minimum stopping distance in the SR 77 bed was 200 feet, and the maximum was 395 feet. The minimum R value was 0.29, while the maximum was 0.41.

STATISTICAL ANALYSIS

The statistical analysis of the testing considers the relationship between the response variables, DISTANCE and R, and the treatment variables SPEED (2-levels), EQUIP (3-levels), and TRACK (2-levels). In the beds at I-17 NB and I-17 SB experimental runs were conducted on three sides of the bed; West, Middle, and East. This additional unplanned source of variation, SIDE, was considered in order to clarify the statistical significance of the other effects.

Two approaches have been taken to analyze the data: 1) each bed was analyzed as a separate factorial experiment using a methodology given in Miliken and Johnson (18), and 2) two factorials were constructed from the 102 runs that were performed. Dr. Rick Burdick of the ASU Business School suggested the factorials that were constructed from the 102 runs. He grouped the East and West runs from the I-17 NB and I-17 SB experiments to fully explore the SIDE effect. The second factorial he constructed included all runs except those performed at SR 77, where only one type of bed preparation equipment was used. Dr. Burdick's analyses are referred to here as the alternative approach.

The alternative approach to analyzing the data came after Dr. Burdick, in a consulting capacity to ADOT, reviewed the statistical analysis performed according to the methodology given by Miliken and Johnson. Dr. Burdick agreed with the Miliken and Johnson approach, but also suggested the other groupings of the data and performed the analysis.

At the time Dr. Burdick reviewed the statistical analysis the only response variable being considered was DISTANCE. Therefore, he performed his analysis using the response variable DISTANCE. His original analysis is presented as an alternative analysis to the ANOVAs that consider the response variable R, for the individual beds.

The analysis of the individual beds was carried out using version 5.18 of SAS on the ASU mainframe. This statistical package was required for the I-17 NB and I-17 SB beds because the analysis matrix was unbalanced and has many missing cells. Although there are methodologies available that estimate missing cells, SAS is the only statistical software known to the author, that has an algorithm to test groups of means on an equivalent basis.

There are six analysis of variances (ANOVA) to follow, one for each of the beds, and the two performed by Dr. Burdick. In the analysis for each of the beds, the I-17 NB and I-17 SB beds required a type IV sum of squares to be used while the other two beds required a type III sum of squares. In SAS a type I and type II sum of squares are generally used for model building approaches to ANOVA (18). The type III and type IV sum of squares are used for means models, or models where the experimenter is trying to determine which treatments significantly affect the response.

P-values for Statistical Testing

In all the analyses given here, the determination of the statistical significance is made based on P-values. The P-value gives the probability of making a type I error, or the probability of rejecting the null hypothesis incorrectly. In general, the null hypothesis is that two groups of means are equal. The type I error rate of $a = 0.05$ indicates that the experimenter is willing to wrongly reject the null hypothesis 5 times out of 100. The P-value gives the actual type I error rate. The type I error rate used for this analysis was $a = 0.05$. P-values smaller than the predetermined type I error rate lead to a rejection of the null hypothesis and the conclusion that the two groups of means are significantly different.

Multiple Comparisons

For this analysis the recommendations of Miliken and Johnson (18) are followed with respect to analyzing three-way and higher order ANOVAs. Miliken and Johnson recommend that the experimenter look for the highest order interaction in the ANOVA table that is statistically significant. Once the highest order significant interaction is determined, the main effect of interest is evaluated within the context of that interaction. For instance, if a two-way interaction is significant, it does not make sense to look only at statistical significance of each main effect without regard to the interaction. Instead, the main effect is examined at both levels of the other treatment. For making these comparisons SAS allows the experimenter to request a Least Squares Means table. This table gives means for the cells of the experimental matrix plus the pairwise comparisons for each of the cell means.

An additional problem that must be considered in determining the statistical significance of higher order interactions is the effect of multiple comparisons. When an experimenter looks at, for example, five two-way interactions to determine if any are statistically significant, five simultaneous comparisons are being made. The chance of finding a significant difference when none exist, a type I error, increases with the number of comparisons. In the worst case, the following equation from basic probability theory would apply:

$$\alpha_o = 1-(1-\alpha_i)^n \qquad (7)$$

Where:

α_o = The desired overall level of protection

α_i = The individual level of protection

n = The number of comparisons.

A very close approximation to the equation (7) is Bonferroni's method which is to make individual comparisons at the α/p level where α is the experimentwise error rate and p is the number of comparisons being made.

For this analysis, all ANOVAs are evaluated according to the Miliken and Johnson methodology for three-way and higher order designs. All statistically significant effects are bolded in the ANOVA tables that follow. In the Least Squares Means tables, not all comparisons are of interest, therefore Bonferroni's method is applied only to selected pairwise comparisons. The selected comparisons are underlined in the Least Squares Means tables and the statistically significant P-values are bolded.

All ANOVA tables were evaluated according to the following:

1. Determine the highest order interaction according to Bonferroni's method considering each order of interaction as a multiple comparison. For instance, if there are 6 two-way interactions and the

overall level of protection is $\alpha = 0.05$ then each two-way interaction was evaluated according to $\alpha_i = 0.0083$.

2. Evaluate the main effect within the context of the interactions through the Least Squares Means and pairwise comparisons table.
3. If the main effect is not involved in any interaction then evaluate it at the $\alpha = 0.05$ level.

SAS Type IV Analysis

For unbalanced data sets with many missing cells, more than one type IV hypothesis is generally possible. SAS builds the contrasts for a type IV sum of squares analysis using an algorithm that is dependent on the order the data are entered. The experimenter knows that SAS is comparing means on an equal basis but does not know which comparisons are being made without requesting the type IV estimable functions. The estimable functions give the contrasts for the ANOVA. For this analysis, the contrasts were requested to determine which groups of means were being compared.

The type IV analyses for I-17 NB and I-17 SB proceeds as follows: 1) the analysis matrix is given to help visualize the distribution of data, 2) the ANOVA table is given, 3) a table giving the groups of means tested for each effect, and 4) a Least Squares Means table is given.

For the I-17 NB data which was taken at two different times, under two different experimental designs, an ANOVA was conducted to determine if the December 1989 data and the Design A 1991 data were significantly different. The result was negative, therefore the data are grouped together in the analysis matrix shown in Table 12. The ANOVA is given in Table 13.

TABLE 12 I-17 NB ANALYSIS MATRIX: RESPONSE VARIABLE R

	Equipment Type																	
	Dozer						Loader						Rake					
	Smooth			Tracked			Smooth			Tracked			Smooth			Tracked		
Speed	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*
45	.35	.34		.26	.25		.31		.29	.25		.24	.29		.27	.25		.21
	.34	.33			.26													
		.33			.28													
65	.38	.35	.32	.31	.28	.28	.29		.29	.26		.25	.29		.25	.26		.25
		.33	.33			.28												
		.35																

Location Within Arrestor Bed: W= West M=Middle E=East

TABLE 13 TYPE IV ANOVA FOR DATA IN TABLE 12

Source of Variation	*df*	*SS*	*F*	*p*
Speed	1*	0.00093346	9.33	**0.0137**
Track	1	0.01839457	183.95	**0.0001**
Equip	2*	0.00951098	47.55	**0.0001**
Side	2*	0.00292218	14.61	**0.0015**
Speed*Track	1*	0.00080633	8.06	0.0194
Speed*Equip	2*	0.00110337	5.52	0.0273
Speed*Side	2*	0.00054846	2.74	0.1175
Track*Equip	2*	0.00165644	8.28	0.0091
Track*Side	2*	0.00018372	0.92	0.4335
Equip*Side	2*	0.00076563	3.83	0.0627
Speed*Track*Equip	2*	0.00008029	0.40	0.6808
Speed*Track*Side	2*	0.00025391	1.27	0.3268
Speed*Equip*Side	1*	0.00000625	0.06	0.8028
Track*Equip*Side	2	0.00000729	0.04	0.9643
Speed*Track*Equip* Side	1	0.00030625	3.06	0.1140

*Other type IV testable hypotheses exist which may yield different *SS*

In Table 13, the four-way interaction was evaluated at the $\alpha = 0.05$ level and therefore the null hypothesis cannot be rejected. The three-way interactions are evaluated at the $\alpha = 0.0125$ level and none of the null hypotheses can be rejected. The two-way interactions are evaluated at the $\alpha = 0.0083$ level, therefore none of the null hypotheses can be rejected. The main effects are evaluated at the $\alpha = 0.05$ level and all are statistically significant.

Table 14 gives the groups of means being tested in Table 13. The following notation is used in Table 14, μ_{ijkl} is the cell mean from Table 12 where the subscripts are as follows:

- i indicates SPEED (1 for 45 and 2 for 65),
- j indicates level of TRACK (1 for Smooth, and 2 for Tracked),

- k indicates EQUIP (1 for Dozer, 2 for Loader, and 3 for Rake), and
- l indicates SIDE (1 for West, 2 for Middle, and 3 for East).

For instance for the cell in Table 12 where the treatment is 45 mph, Smooth, Dozer, West the notation would be μ_{1111}.

TABLE 14 TYPE IV HYPOTHESIS TESTED FOR ANOVA IN TABLE 13

Source of Variation	*Hypothesis*
Speed	$\mu_{1111} + \mu_{1112} + \mu_{1121} + \mu_{1123} + \mu_{1131} + \mu_{1133} + \mu_{1211} + \mu_{1212} + \mu_{1221} + \mu_{1223} + \mu_{1231} + \mu_{1233} = \mu_{2111} + \mu_{2112} + \mu_{2121} + \mu_{2123} + \mu_{2131} + \mu_{2133} + \mu_{2211} + \mu_{2212} + \mu_{2221} + \mu_{2223} + \mu_{2231} + \mu_{2233}$
Tracking	$\mu_{1111} + \mu_{1112} + \mu_{1121} + \mu_{1123} + \mu_{1131} + \mu_{1133} + \mu_{2111} + \mu_{2112} + \mu_{2113} + \mu_{2121} + \mu_{2123} + \mu_{2131} + \mu_{2133} = \mu_{1211} + \mu_{1212} + \mu_{1221} + \mu_{1223} + \mu_{1231} + \mu_{1233} + \mu_{2211} + \mu_{2212} + \mu_{2213} + \mu_{2221} + \mu_{2223} + \mu_{2231} + \mu_{2233}$
Equipment	$\mu_{1111} + \mu_{1211} + \mu_{2111} + \mu_{2113} + \mu_{2211} + \mu_{2213} = \mu_{1131} + \mu_{1231} + \mu_{2131} + \mu_{2133} + \mu_{2231} + \mu_{2233}$ **and** $\mu_{1121} + \mu_{1123} + \mu_{1221} + \mu_{1223} + \mu_{2121} + \mu_{2123} + \mu_{2221} + \mu_{2223} = \mu_{1131} + \mu_{1133} + \mu_{1231} + \mu_{1233} + \mu_{2131} + \mu_{2133} + \mu_{2231} + \mu_{2233}$
Side	$\mu_{1121} + \mu_{1131} + \mu_{1221} + \mu_{1231} + \mu_{2111} + \mu_{2121} + \mu_{2131} + \mu_{2211} + \mu_{2221} + \mu_{2231} = \mu_{1123} + \mu_{1133} + \mu_{1223} + \mu_{1233} + \mu_{2113} + \mu_{2123} + \mu_{2133} + \mu_{2213} + \mu_{2223} + \mu_{2233}$ **and** $\mu_{2112} + \mu_{2212} = \mu_{2113} + \mu_{2213}$
*Speed*Track*	$\mu_{1111} + \mu_{1112} + \mu_{1121} + \mu_{1123} + \mu_{1131} + \mu_{1133} + \mu_{2211} + \mu_{2212} + \mu_{2221} + \mu_{2223} + \mu_{2231} + \mu_{2233} = \mu_{1211} + \mu_{1212} + \mu_{1221} + \mu_{1223} + \mu_{1231} + \mu_{1233} + \mu_{2111} + \mu_{2112} + \mu_{2121} + \mu_{2123} + \mu_{2131} + \mu_{2133}$
*Speed*Equip*	$\mu_{1111} + \mu_{1211} + \mu_{2131} + \mu_{2231} = \mu_{1131} + \mu_{1231} + \mu_{2111} + \mu_{2211}$ **and** $\mu_{1121} + \mu_{1123} + \mu_{1221} + \mu_{1223} + \mu_{2131} + \mu_{2133} + \mu_{2231} + \mu_{2233} = \mu_{1131} + \mu_{1133} + \mu_{1231} + \mu_{1233} + \mu_{2121} + \mu_{2123} + \mu_{2221} + \mu_{2223}$
*Speed*Side*	$\mu_{1212} + \mu_{1231} + \mu_{2211} + \mu_{2233} = \mu_{1211} + \mu_{1233} + \mu_{2212} + \mu_{2231}$ **and** $\mu_{1121} + \mu_{1131} + \mu_{1221} + \mu_{1231} + \mu_{2123} + \mu_{2133} + \mu_{2223} + \mu_{2233} = \mu_{1123} + \mu_{1133} + \mu_{1223} + \mu_{1233} + \mu_{2121} + \mu_{2131} + \mu_{2221} + \mu_{2231}$
*Track*Equip*	$\mu_{1111} + \mu_{1231} + \mu_{2111} + \mu_{2113} + \mu_{2231} + \mu_{2233} = \mu_{1131} + \mu_{1211} + \mu_{2131} + \mu_{2133} + \mu_{2211} + \mu_{2213}$ **and** $\mu_{1121} + \mu_{1123} + \mu_{1233} + \mu_{2121} + \mu_{2123} = \mu_{1133} + \mu_{1221} + \mu_{1223} + \mu_{2221} + \mu_{2223}$
*Track*Side*	$\mu_{2112} + \mu_{2213} = \mu_{2113} + \mu_{2212}$ **and** $\mu_{1121} + \mu_{1131} + \mu_{1223} + \mu_{1233} + \mu_{2111} + \mu_{2121} + \mu_{2131} + \mu_{2213} + \mu_{2223} + \mu_{2233} = \mu_{1123} + \mu_{1133} + \mu_{1221} + \mu_{2113} + \mu_{2123} + \mu_{2133} + \mu_{2211} + \mu_{2221} + \mu_{2231}$

TABLE 14 (Continued)

*Equip*Side*	$\mu_{2111} + \mu_{2133} + \mu_{2211} + \mu_{2233} = \mu_{2113} + \mu_{2131} + \mu_{2213} + \mu_{2231}$ **and** $\mu_{1121} + \mu_{1133} + \mu_{1221} + \mu_{1233} + \mu_{2121} + \mu_{2133} + \mu_{2221} + \mu_{2233} = \mu_{1123} + \mu_{1131} + \mu_{1223} + \mu_{1231} + \mu_{2123} + \mu_{2131} + \mu_{2223} + \mu_{2231}$
*Speed*Tack*Equip*	$\mu_{1111} + \mu_{1231} + \mu_{2131} + \mu_{2211} = \mu_{1133} + \mu_{1211} + \mu_{2111} + \mu_{2231}$ **and** $\mu_{1121} + \mu_{1123} + \mu_{1231} + \mu_{1233} + \mu_{2133} + \mu_{2221} + \mu_{2223} = \mu_{1133} + \mu_{1221} + \mu_{1223} + \mu_{2121} + \mu_{2123} + \mu_{2231} + \mu_{2233}$
*Speed*Track*Side*	$\mu_{1112} + \mu_{1131} + \mu_{1211} + \mu_{1233} + \mu_{2111} + \mu_{2133} + \mu_{2212} + \mu_{2231} = \mu_{1111} + \mu_{1133} + \mu_{1212} + \mu_{1231} + \mu_{2112} + \mu_{2131} + \mu_{2211} + \mu_{2233}$ **and** $\mu_{1121} + \mu_{1131} + \mu_{1223} + \mu_{1233} + \mu_{2123} + \mu_{2133} + \mu_{2221} + \mu_{2231} = \mu_{1123} + \mu_{1133} + \mu_{1221} + \mu_{1231} + \mu_{2121} + \mu_{2131} + \mu_{2223} + \mu_{2233}$
*Speed*Equip*Side*	$\mu_{1121} + \mu_{1133} + \mu_{1221} + \mu_{1233} + \mu_{2123} + \mu_{2131} + \mu_{2223} + \mu_{2231} = \mu_{1123} + \mu_{1131} + \mu_{1223} + \mu_{1231} + \mu_{2121} + \mu_{2133} + \mu_{2221} + \mu_{2233}$
*Track*Equip*Side*	$\mu_{2111} + \mu_{2133} + \mu_{2213} + \mu_{2231} = \mu_{2113} + \mu_{2131} + \mu_{2211} + \mu_{2233}$ **and** $\mu_{1121} + \mu_{1133} + \mu_{1223} + \mu_{1231} + \mu_{2121} + \mu_{2133} + \mu_{2223} + \mu_{2231} = \mu_{1123} + \mu_{1131} + \mu_{1221} + \mu_{1233} + \mu_{2123} + \mu_{2131} + \mu_{2221} + \mu_{2233}$
*Speed*Track*Equip* Side*	$\mu_{1121} + \mu_{1133} + \mu_{1223} + \mu_{1231} + \mu_{2123} + \mu_{2131} + \mu_{2221} + \mu_{2233} = \mu_{1123} + \mu_{1131} + \mu_{1221} + \mu_{1233} + \mu_{2121} + \mu_{2133} + \mu_{2223} + \mu_{2231}$

Miliken and Johnson advise that in some cases the hypothesis tested by type IV sum of squares may not be of interest. A careful examination of Table 14 shows that the hypothesis tested are of interest although they not are exhaustive. For instance, there are simultaneous comparisons being made to determine the effect of SIDE, that is, two groups of means are being compared at the same time, leading to uncertainty about whether both comparisons are significantly different or whether only one comparison is significantly different. An examination of the analysis matrix, Table 12, shows that, at all EQUIP levels, and both SPEED levels except Dozer 45, the SIDE comparison is possible between the East and West. Hence, the 10 means on the West are compared with the 10 means on the East as shown in Table 14 in the SIDE row. Additionally, the Dozer 45 mph West (Smooth and Tracked grouped together) is compared to the Dozer 45 mph Middle (Smooth and Tracked grouped together). This accounts for the two groups of means being tested. The additional comparisons possible for SIDE, not tested in ANOVA, are the Dozer 65 mph, West and East compared to the Middle. To make this comparison and further explore the SPEED main effect, the Least Squares Means and pairwise comparisons are shown in Table 15.

TABLE 15 THREE-WAY LEAST SQUARES MEANS (SPEED*EQUIP*SIDE), AND PAIRWISE COMPARISONS FOR DATA IN TABLE 12

Pop. Cell Mean	Least Sqs. Mean	Std. Error	45 Dozer West	45 Dozer Midd.	45 Load. West	45 Load. East	45 Rake West	45 Rake East	65 Dozer West	65 Dozer Midd.	65 Dozer East	65 Load. West	65 Load. East	65 Rake West	65 Rake East
45 Dozer West	0.3025	0.0061		0.5851	0.0395	0.0031	0.0070	0.0001	[2] **0.0014**	0.3044	1.0000	0.0165	0.0070	0.0165	0.0003
45 Dozer Midd.	0.2983	0.0041			0.0514	0.0027	0.0070	0.0001	0.0003	[2] 0.0920	0.5347	0.0188	0.0070	0.0188	0.0002
45 Load. West	0.2800	0.0071				0.1679	0.3434	0.0031	0.0001	0.0071	0.0288	[2] 0.6291	0.3434	0.6291	0.0150
45 Load. East	0.2650	0.0071					0.6291	0.0339	0.0001	0.0006	0.0019	0.3434	[2] 0.6291	0.3434	0.1679
45 Rake West	0.2700	0.0071						0.0150	0.0001	0.0014	0.0045	0.6291	1.0000	[2] 0.6291	0.0766
45 Rake East	0.2400	0.0071							0.0001	0.0001	0.0001	0.0067	0.0150	0.0067	[2] 0.3434
65 Dozer West	0.3450	0.0071								[1] **0.0053**	[1] **0.0008**	0.0001	0.0001	0.0001	0.0001
65 Dozer Midd.	0.3117	0.0058									[1] 0.2607	0.0030	0.0014	0.0030	0.0001
65 Dozer East	0.3025	0.0050										0.0113	0.0045	0.0113	0.0002
65 Load. West	0.2750	0.0071											0.6291	1.0000	0.0339
65 Load. East	0.2700	0.0071												0.6291	0.0766
65 Rake West	0.2750	0.0071													0.0339
65 Rake East	0.2500	0.0071													

There are 9 comparisons of interest in Table 15. Three of the pairwise comparisons deal with SIDE, and six deal with SPEED. Because there are 9 comparisons of interest the P-values were evaluated according to $\alpha = 0.0056$. The three comparisons dealing with the SIDE effect are clustered left of the SPEED comparisons which are on a diagonal slanting to the right.

The SIDE comparison in Table 15 indicates that the 65 mph Dozer West is statistically different from both the Middle and East, but the Middle and East are not statistically different from each other. It is interesting to note from Table 14 for the Least Squares Means column that in all cases as the runs move from West to East the mean R value decreases. Of the 6 SPEED comparisons, only the Dozer West treatment shows a statistical difference between the 45 mph and 65 mph.

Next the data from I-17 SB were analyzed. Table 16 presents the analysis matrix and Table 17 presents the ANOVA. Table 16 shows the dispersion of observations within the analysis matrix. The ANOVA was conducted using the same methodology as the I-17 NB analysis.

TABLE 16 I-17 SB ANALYSIS MATRIX: RESPONSE VARIABLE R

	Equipment Type																	
	Dozer						Loader						Rake					
	Smooth			Tracked			Smooth			Tracked			Smooth			Tracked		
Speed	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*	*W*	*M*	*E*
45	.26		.25	.23		.22	.29	.24		.25	.20		.27	.23		.24	.19	
65		.30 .31			.28				.30 .30			.25 .26		.28	.30		.25	.26

TABLE 17 TYPE IV ANOVA FOR DATA IN TABLE 16

Source of Variation	*df*	*SS*	*F*	*p*
Speed	1*	0.00302500	90.75	**0.0025**
Track	1	0.00662162	198.65	**0.0008**
Equip	2*	0.00028487	4.27	0.1324
Side	2*	0.00032500	4.87	0.1141
Speed*Track	1	0.00002500	0.75	0.4502
Speed*Equip	0	NTH**		
Speed*Side	0	NTH**		
Track*Equip	2*	0.00002882	0.43	0.6839
Track*Side	2*	0.00002500	0.37	0.7155
Equip*Side	2*	0.00001250	0.37	0.5836
Speed*Track*Equip	0	NTH**		
Speed*Track*Side	0	NTH**		
Speed*Equip*Side	0	NTH**		
Track*Equip*Side	2	0.00001250	0.37	0.5836
Speed*Track*Equip* Side	1	0.00000000		

*Other type IV testable hypothesis exist which may yield different *SS*

**No Testable Hypothesis

The ANOVA indicates no significant interactions, for which a test was possible, and only the main effects SPEED and TRACK are significant. Table 18 gives the groups of means tested in Table 17. Table 18 shows that there are only 4 means involved in the test for SPEED. The 4 cell means tested are 45 mph Rake (Smooth and Tracked) Middle, compared to the 65 mph Rake (Smooth and Tracked) Middle. There are two simultaneous comparisons for SIDE, each consisting of 4 cell means. One is the 45 mph Dozer (East compared to West) and the other is the 65 mph Rake (Middle compared to East). The tests for SPEED and SIDE are based on a comparatively small number of cell means and may not be very meaningful.

Two additional hypotheses remain for the SIDE effect: 1) Loader 45 mph (West versus Middle) and 2) Rake 45 mph (West versus Middle). To make the other two comparisons as well as to determine if the two tests conducted simultaneously by the ANOVA are statistically significant, the Least Squares Means table was requested for the SPEED*EQUIP*SIDE combination. Table 19 shows the results.

TABLE 18 TYPE IV HYPOTHESIS TESTED FOR ANOVA IN TABLE 16

Source of Variation	*Hypothesis*
Speed	$\mu_{1132} + \mu_{1232} = \mu_{2132} + \mu_{2232}$
Tracking	$\mu_{1111} + \mu_{1113} + \mu_{1121} + \mu_{1122} + \mu_{1131} + \mu_{1132} + \mu_{2112} + \mu_{2123} + \mu_{2132} + \mu_{2133} = \mu_{1211} + \mu_{1213} + \mu_{1221} + \mu_{1222} + \mu_{1231} + \mu_{1232} + \mu_{2212} + \mu_{2223} + \mu_{2232} + \mu_{2233}$
Equipment	$\mu_{1111} + \mu_{1211} + \mu_{2112} + \mu_{2212} = \mu_{1131} + \mu_{1231} + \mu_{2132} + \mu_{2232}$ **and** $\mu_{1121} + \mu_{1122} + \mu_{1221} + \mu_{1222} + \mu_{2123} + \mu_{2223} = \mu_{1131} + \mu_{1132} + \mu_{1231} + \mu_{1232} + \mu_{2133} + \mu_{2233}$
Side	$\mu_{1111} + \mu_{1211} = \mu_{1113} + \mu_{1213}$ **and** $\mu_{2132} + \mu_{2232} = \mu_{2133} + \mu_{2233}$
*Speed*Track*	$\mu_{1132} + \mu_{2232} = \mu_{1232} + \mu_{2132}$
*Track*Equip*	$\mu_{1111} + \mu_{1231} + \mu_{2112} + \mu_{2232} = \mu_{1131} + \mu_{1211} + \mu_{2132} + \mu_{2212}$ **and** $\mu_{1121} + \mu_{1122} + \mu_{1231} + \mu_{1232} + \mu_{2123} + \mu_{2233} = \mu_{1131} + \mu_{1132} + \mu_{1221} + \mu_{1222} + \mu_{2133} + \mu_{2223}$
*Track*Side*	$\mu_{1111} + \mu_{1213} = \mu_{1113} + \mu_{1211}$ **and** $\mu_{2132} + \mu_{2233} = \mu_{2133} + \mu_{2232}$
*Equip*Side*	$\mu_{1121} + \mu_{1132} + \mu_{1221} + \mu_{1232} = \mu_{1122} + \mu_{1131} + \mu_{1222} + \mu_{1231}$
*Track*Equip*Side*	$\mu_{1121} + \mu_{1132} + \mu_{1222} + \mu_{1231} = \mu_{1122} + \mu_{1131} + \mu_{1221} + \mu_{1232}$

TABLE 19 THREE-WAY LEAST SQUARES MEANS (SPEED*EQUIP*SIDE), AND PAIRWISE COMPARISONS FOR DATA IN TABLE 16

Pop. Cell Mean	Least Sqs. Mean	Std. Error	45 Dozer West	45 Dozer East	45 Loader West	45 Loader Middle	45 Rake West	45 Rake Middle	65 Dozer Middle	65 Loader East	65 Rake Middle	65 Rake East
45 Dozer West	0.245	0.004		0.1817	0.0227	0.0227	0.1817	0.0090	0.0031	0.0074	0.0405	0.0090
45 Dozer East	0.235	0.004			0.0090	0.0805	0.0405	0.0227	0.0018	0.0034	0.0138	0.0044
45 Loader West	0.270	0.004				**0.0032**	0.0805	0.0019	0.0252	0.2306	0.4502	0.1817
45 Loader Middle	0.220	0.004					0.0090	0.1817	0.0009	0.0014	0.0044	0.0019
45 Rake West	0.255	0.004						**0.0044**	0.0061	0.0205	0.1817	0.0227
45 Rake Middle	0.210	0.004							0.0006	0.0009	0.0025	0.0012
65 Dozer Middle	0.293	0.004								0.0462	0.0146	0.1036
65 Loader East	0.278	0.003									0.0877	0.6514
65 Rake Middle	0.265	0.004										0.0805
65 Rake East	0.280	0.004										

The pairwise comparisons indicate neither of the simultaneous comparisons for SIDE in the ANOVA are statistically significant. However, the two additional tests, 45 mph Loader (West compared to Middle) and 45 mph Rake (West compared to Middle) are both statistically significant. Also note the runs in the Middle of the bed consistently had the lowest R values. It was noted in the testing observations that the bed had a somewhat concave shape indicating a thinning in the Middle of the bed.

US 89 Type III Analysis

The analysis for the US 89 bed and the SR 77 bed consisted of a type III sum of squares ANOVA which is equivalent to the type IV when all cells are observed at least once. Table 20 presents the analysis matrix for US 89 and Table 21 presents the ANOVA.

TABLE 20 US 89 ANALYSIS MATRIX: RESPONSE VARIABLE R

	Equipment					
	Dozer		Loader		Rake	
Speed	Smooth	Tracked	Smooth	Tracked	Smooth	Tracked
45	.30	.24	.32	.26	.29	.26
	.29	.25	.29	.24	.30	.25
65	.29	.26	.29	.28	.30	.27
	.30	.27	.29	.27	.31	.28

TABLE 21 TYPE III ANOVA FOR DATA IN TABLE 20

Source of Variation	*df*	*SS*	*F*	*p*
Speed	1	0.0006000	6.55	**0.0251**
Track	1	0.0080667	88.00	**0.0001**
Equip	2	0.0002333	1.27	0.3153
Speed*Track	1	0.0008167	8.91	**0.0114**
Speed*Equip	2	0.0001000	0.55	0.5933
Track*Equip	2	0.0003333	0.18	0.8360
Speed*Track*Equip	2	0.0023333	1.27	0.3153

The ANOVA table indicates that the SPEED*TRACK interaction is significant. SPEED and TRACK are the only significant main effects. The SPEED*TRACK Least Squares Means, and pairwise comparisons are presented in Table 22. There are two comparisons of interest here: 45 mph Smooth compared to 65 mph Smooth, and 45 mph Tracked compared to 65 mph Tracked. These means are compared at the α=0.025 level. The P-values indicate that at the Smooth level there is no effect on R due to SPEED and at the Tracked level there is an effect on R due to SPEED.

TABLE 22 TWO-WAY LEAST SQUARES MEANS (SPEED*TRACK), AND PAIRWISE COMPARISONS FOR DATA IN TABLE 20

Pop. Cell Mean	*Least Squares Means*	*Std. Errors*	*45 Smooth*	*45 Tracked*	*65 Smooth*	*65 Tracked*
45 Smooth	0.2967	0.0045		0.0001	0.7682	0.0004
45 Tracked	0.2517	0.0045			0.0001	**0.0020**
65 Smooth	0.2950	0.0045				0.0007
65 Tracked	0.2728	0.0045				

SR 77 Type III Analysis

The analysis for SR 77 proceeds the same as for US 89. The analyses matrix is presented in Table 23 and the ANOVA is presented in Table 24.

TABLE 23 SR 77 ANALYSIS MATRIX: RESPONSE VARIABLE R

	Track	
Speed	Smooth	Tracked
45	.36	.30
	.36	.29
65	.40	.35
	.41	.37

TABLE 24 TYPE III ANOVA FOR DATA IN TABLE 23

Source of Variation	*df*	*SS*	*F*	*p*
Speed	1	0.00605	80.67	**0.0009**
Track	1	0.00605	80.67	**0.0009**
Speed*Track	1	0.00020	2.67	0.1778

In the SR 77 ANOVA the SPEED*TRACK interaction is not statistically significant, indicating that the level of TRACK does not effect whether a 45 mph entry velocity produced a different R value than a 65 mph entry velocity as it did at US 89. The Least Squares Means and pairwise comparisons given in Table 25, indicate a significant difference between both the 45 mph Smooth and 65 mph Smooth, and the 45 mph Tracked and 65 mph Tracked.

TABLE 25 TWO-WAY LEAST SQUARES MEANS (SPEED*TRACK), AND PAIRWISE COMPARISONS FOR DATA IN TABLE 23

Pop. Cell Mean	*Least Squares Means*	*Std. Errors*	*45 Smooth*	*45 Tracked*	*65 Smooth*	*65 Tracked*
45 Smooth	0.3600	0.0061		0.0017	**0.0065**	1.0000
45 Tracked	0.2950	0.0061			0.0002	**0.0017**
65 Smooth	0.4050	0.0061				0.0065
65 Tracked	0.3600	0.0061				

Alternative Analysis

The alternative analysis performed by Dr. Burdick is now given. The analysis which contains the East and West SIDE runs from I-17 NB and I-17 SB is presented first. Dr. Burdick used this ANOVA to determine if the SIDE effect was significant. This data set contains missing cells, however, by specifying a model that does not include interactions of higher than second order, the hypothesis are the same for the type III and type IV sum of squares. The ANOVA is presented in Table 26.

TABLE 26 TYPE III ANOVA FOR I-17 NB AND I-17 SB, EAST AND WEST SIDE ONLY

Source of Variation	*df*	*SS*	*F*	*p*
Speed	1	345938.704	445.51	**0.0001**
Track	1	33548.195	43.20	**0.0001**
Equip	2	14309.076	9.21	**0.0009**
Side	1	3566.933	4.59	**0.0413**
Bed	1	26068.540	33.57	**0.0001**
Speed*Side	1	315.230	0.41	0.5294
Bed*Side	1	85.313	0.11	0.7429
Track*Side	1	209.271	0.27	0.6079
Equip*Side	2	773.189	0.50	0.6133

SIDE was the main effect of interest in this data set. For this data set third order interactions were not considered important. The second order interactions were considered at the α/p value of 0.0125. As can be seen from the Table 26 none of the interactions are significant and therefore the main effects are evaluated. The SIDE effect is evaluated at the α=0.05 level. Table 26 shows that SIDE is significant.

The next data set Dr. Burdick formed included all runs except those performed at SR 77. Table 27 presents the ANOVA.

TABLE 27 TYPE III ANOVA FOR ALL RUNS EXCEPT SR 77

Source of Variation	*df*	*SS*	*F*	*p*
Speed	1	1012396.289	2248.02	**0.0001**
Track	1	56483.215	125.42	**0.0001**
Equip	2	11714.102	13.01	**0.0001**
Bed	2	49867.974	55.37	**0.0001**
Speed*Track	1	603.983	1.34	0.2528
Speed*Equip	2	4660.261	5.17	0.0094
Track*Equip	2	231.717	0.26	0.7743
Speed*Bed	2	3315.960	3.68	0.0329
Track*Bed	2	1100.100	1.22	0.3042
Equip*Bed	4	18901.753	10.04	**0.0001**
Speed*Track*Bed	2	371.053	0.41	0.6648
Speed*Equip*Bed	4	675.576	0.38	0.8253
Track*Equip*Bed	4	2743.968	1.52	0.2111
Speed*Track*Equip	2	129.231	0.14	0.8667
Speed*Track*Equip*Bed	4	764.177	0.42	0.7903

The third and fourth order interactions are not significant and only the second order interactions are considered as a first step. There are 6 second order interactions evaluated according to $\alpha/p = 0.0083$. According to the pairwise comparison rule, followed throughout this analysis, there is only one significant interaction, BED*EQUIP. However, the SPEED*EQUIP and SPEED*BED interactions had small P-values and the pairwise comparisons were made for all three interactions as shown in Tables 28, 29, and 30.

TABLE 28 TWO-WAY LEAST SQUARES MEANS (SPEED*EQUIP), AND PAIRWISE COMPARISONS FOR ALL RUNS EXCEPT SR 77

Pop. Cell Mean	*Least Squares Means*	*Std. Errors*	*45 Dozer*	*45 Loader*	*45 Rake*	*65 Dozer*	*65 Loader*	*65 Rake*
45 Dozer	285.67	5.54		.8097	.0563	.0001	.0001	.0001
45 Loader	287.67	6.13			.1088	.0001	.0001	.0001
45 Rake	301.83	6.13				.0001	.0001	.0001
65 Dozer	497.43	6.04					**.0001**	**.0001**
65 Loader	536.33	6.13						.6533
65 Rake	540.25	6.13						

TABLE 29 TWO-WAY LEAST SQUARES MEANS (SPEED*BED), AND PAIRWISE COMPARISONS FOR ALL RUNS EXCEPT SR 77

Pop. Cell Mean	*Least Squares Means*	*Std. Errors*	*45 US 89*	*45 I-17 NB*	*45 I-17 SB*	*65 US 89*	*65 I-17 NB*	*65 I-17 SB*
45 US 89	280.083	6.126		0.0194	**0.0001**	0.0001	0.0001	0.0001
45 I-17 NB	260.083	5.536			**0.0001**	0.0001	0.0001	0.0001
45 I-17 SB	335.000	6.126				0.0001	0.0001	0.0001
65 US 89	526.583	6.126					**0.0014**	0.0170
65 I-17 NB	498.514	5.498						**0.0001**
65 I-17 SB	548.917	6.617						

Table 28 indicates that at 45 mph, there is no difference between any of the equipment types. However, at 65 mph, the Dozer is different from both the Loader and the Rake, which are not different from each other.

Table 29 indicates that at 45 mph, the stopping distances for I-17 SB were greater than for I-17 NB and US 89, which were not significantly different. At 65 mph, I-17 NB produced the shortest stopping distances, while for I-17 SB and US 89 there was no statistical difference.

TABLE 30 TWO-WAY LEAST SQUARES MEANS (EQUIP*BED), AND PAIRWISE COMPARISONS FOR ALL RUNS EXCEPT SR 77

Pop. Cell Mean	*Least Squar. Means*	*Std. Errors*	*Dozer US 89*	*Dozer I-17 NB*	*Dozer I-17 SB*	*Load. US 89*	*Load. I-17 NB*	*Load. I-17 SB*	*Rake US 89*	*Rake I-17 NB*	*Rake I-17 SB*
Dozer US 89	410.38	7.50		.0001	.2002	.4832	.0498	.0026	.2055	.9440	.0001
Dozer I-17 NB	339.27	4.94			.0001	.0001	**.0001**	.0001	.0001	**.0001**	.0001
Dozer I-17 SB	425.27	8.39				.0554	.0025	.0960	.0156	.1785	.0070
Load. US 89	402.88	7.50					.1975	.0003	.5666	.5278	.0001
Load. I-17 NB	389.00	7.50						.0001	.4689	.0581	.0001
Load. I-17 SB	444.13	7.50							.0001	.0022	.2402
Rake US 89	396.75	7.50								.2312	.0001
Rake I-17 NB	409.63	7.50									.0001
Rake I-17 SB	456.75	7.50									

Table 30 indicates that at US 89 and I-17 SB there was no difference in stopping distance between the equipment types. In the I-17 NB bed the Dozer produced significantly shorter stopping distances than either the Rake or Loader, which were not significantly different.

Statistical Analysis Summary

The variables that were analyzed here include the planned variables, SPEED, EQUIP, and TRACK. Additionally, there were the unplanned variables, SIDE and BED. Two response variable were used, R and DISTANCE. The analyses using R were performed considering the runs at each bed as a separate experiment. The analyses using DISTANCE were performed on selected groupings of the data. All the results are reported in Table 31.

TABLE 31 STATISTICAL ANALYSIS SUMMARY

EFFECT	I-17 NB Type IV R=RESP.	I-17 SB Type IV R=RESP.	US 89 Type III R=RESP.	SR 77 Type III R=RESP.	I-17 NB & SB East & West Type III Distance= RESP.	All Except SR 77 Distance= RESP.	I-17 NB & SB R=RESP.	All Except 77 R=RESP.
BED	NA	NA	NA	NA	**0.0001**	**0.0001**	**0.0235**	**0.0001**
SPEED	**0.0137**	**0.0025**	**0.0251**	**0.0009**	**0.0001**	**0.0001**	**0.0075**	**0.0001**
SIDE	**0.0015**	0.1141	NA	NA	**0.0413**	**NA**	0.0832	**NA**
EQUIP	**0.0001**	0.1324	0.3153	NA	**0.0009**	**0.0001**	**0.0070**	**0.0002**
TRACK	**0.0001**	**0.0008**	**0.0001**	**0.0009**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
SPEED* TRACK	**0.0194**	0.4502	**0.0114**	0.1778	NA	0.2528	NA	**0.0283**
BED* EQUIP	NA	NA	NA	NA	NA	**0.0001**	NA	**0.0001**
SPEED* BED	NA	NA	NA	NA	NA	**0.0329**	NA	**0.0006**

*NA indicates not applicable or not tested for
Note: all effects are evaluated at $\alpha = 0.05$

INTERPRETATION OF STATISTICAL ANALYSIS

The analyses indicated that all the main effects were significant including the unplanned treatment SIDE. The following presents possible interpretations of the statistical analysis and evaluations of tests considered in the statistical analysis, such as double tracking and a comparison between SR 77 and the other beds.

Main Effects

The main effects were SPEED, EQUIP, TRACK, and SIDE. The main effects were analyzed with respect to the response variables R and DISTANCE. The analysis using DISTANCE as the response variable was carried by Dr. Burdick.

Speed

It seems obvious that SPEED treatment would significantly effect the stopping distance. However, when SPEED is evaluated with respect to the response variable R it provides a means to determine if the rolling resistance (R) increases or decreases with entry velocity. In the I-17 NB ANOVA SPEED was significant. However, when examining the pairwise comparisons, SPEED was significant only for the Dozer West treatment. The analysis for I-17 NB also indicated that the Dozer West treatments produced the largest R values, and hence the shortest stopping distances.

In the I-17 SB bed it was not possible to make any definitive conclusions, with respect to SPEED, due to the dispersion in the data. In the US 89 ANOVA SPEED was significant, however the pairwise comparisons revealed that SPEED was only significant at the Tracked level. The comparison of US 89 to the other beds is confounded by the lack of scarification of the US 89 bed.

The ANOVA from the SR 77 bed indicated that SPEED was significant both at the Smooth and Tracked levels. The experiment at SR 77 had the least amount of "noise" of any experiment conducted. The Dozer, which can be said to perform best when used properly, was the only equipment used at SR 77 and no SIDE runs were conducted. Therefore, the SR 77 gives the most reliable data on SPEED.

The SR 77 bed has the greatest gravel depth, and gravel depth gradient. The SR 77 has a vertical curve that transitions the initial negative grade to a positive grade. Therefore, as the entry velocity increases the average gravel depth and positive grade increases. The effect of SPEED on R and distance traveled is therefore attributed to the gravel depth and grade.

Track

The TRACK effect was significant in all statistical analyses. There are two possible causes for the TRACK effect: 1) the gravel was compacted by the truck tires, and 2) the gravel depth decreased due to tire ruts. Three of the beds had the same gravel type while the other had the smaller pea gravel. Both gravel types used in Arizona arrestor beds are highly rounded, although by observation, the pea gravel in the US 89 bed appears somewhat less round than the aggregates in the other beds. Perfectly rounded particles cannot be compacted. However, any deviation from perfectly rounded particles could result in a more dense configuration upon loading. Therefore, if the effect due to tracking was greater at US 89 than at the other beds, a case could be made for aggregate compaction. The decrease in R due to tracking at US 89 was 12.34 percent, whereas the decrease in R due to tracking at SR 77 was 14.38 percent. Therefore, we cannot conclude that there is a compaction effect based on this comparison.

The effect of decreased bed depth on R due to tracking is also plausible. The best way to determine whether the decrease in depth is causing the TRACK effect is to compare the I-17 NB and SR 77 beds. These two beds are the most similar of all beds tested with respect to grade and aggregate type. They do however, have a large difference in bed depth. The relative decrease in bed depth at I-17 NB would be greater than the relative decrease in bed depth at SR 77. To make the comparison only the Middle runs in both beds of the Dozer preparation were compared. The decrease in R due to tracking at I-17 NB is 20.7 percent while at the SR 77 the decrease is 14.4 percent. We can conclude from this comparison that the tracking effect is largely due to decreased gravel depth.

Another source of information about the tracking effect comes from the double tracked runs performed as part of the testing but not included in the statistical analysis. Double tracked runs are performed in the ruts of a TRACK run. In the I-17 NB December 1989 testing a set of runs, number 8, 9, and 10, were conducted that consisted of an initial Dozer 65 mph followed by two runs at 45 mph in the same tracks. The stopping distances and subsequent R values were 411 feet (R=0.35), 253 feet (R=0.27), and 260 feet (R=0.26).

In the I-17 NB 1991 testing two sets of double tracked runs were made, one at 45 mph and one at 65 mph. Runs number 1,2, and 3 were Dozer 45 mph, and produced stopping distances and subsequent R values of 204 feet (R=0.35), 266 feet (R=0.26), and 278 feet (R=0.27). Runs number 5, 6, and 7 were Dozer 65 mph and produced stopping distances and subsequent R values of 395 feet (R=0.32), 485 feet (R=0.28), and 516 feet (R=0.28). Run number 7 was 31 feet longer than run number 6 but still produced the same R value because the R value was calculated based on the actual entry velocity as measured by the radar. Run number 7 was 1.5 mph over the target entry velocity of 65 mph.

The testing at US 89 also included one set of double tracked runs. The runs were Rake 45 mph and included runs number 13, 14, and 15. The stopping distances and subsequent R values were 251 feet (R=0.30), 303 feet (R=0.25), and 318 (R=0.23). The average decrease in R due to single tracking for these three sets of double tracked runs was 0.06 and the average decrease due to an additional run in the same tracks was 0.01. Double tracking does not appear to greatly decrease the stopping power of the aggregate over single tracking. Deeper penetration by the truck tires during double tracked runs was not observed. Therefore, it was concluded that the small increase in R for double tracking was due to some small compaction of the aggregate. The effect of compaction is small, that is, aggregate that are generally rounded do not compact to any great extent.

Equipment

Equipment type was shown to be significant in the I-17 NB bed where the equipment operator was experienced and did what appeared to be an excellent job. In the other two beds where different types of equipment were used, either the equipment operators were somewhat less experienced or the equipment was not properly configured, such as the lack of rippers on the dozer at the US 89 bed.

Side

The SIDE effect was determined to be significant in the I-17 NB bed but not the I-17 SB bed. It was noted that the I-17 SB bed had a concave surface that extended from the beginning of the bed to about 50 feet and from side to side. In the I-17 NB bed it was noted from Table 15 that the R, Least Squares Means for SPEED*EQUIP*SIDE always decreased from West to East. For both beds the West side of the bed is the unconfined side, while the East side is confined by the access road. For the I-17 SB bed the R value, in Table 19 decreases as the runs move from West to East, except for the 65 mph Rake Middle which was 0.265 and the 65 mph Rake East which was 0.280. This can be explained by the decreased depth in the Middle of I-17 SB due to the concave surface near the entrance of the bed.

It was originally hypothesized that the SIDE effect was due to the effect of aggregate confinement in the beds. In other words aggregate that are confined by some pressure will withstand a greater loading before deforming than an aggregate with no confining pressure. However, the confining pressures on the aggregate are small. It is more likely that some edge effect due to the access road in combination with variations in aggregate depth and grade are responsible for the SIDE effect.

Two-Way Interaction

The only two-way interaction that provides any insight into the mechanisms of arrestor bed performance is SPEED*BED. In the analysis by Dr. Burdick the stopping distance was always statistically different for 45 mph entry velocity and 65 mph entry velocity. A comparison based on R was performed to remove the effects of grade and scale the data. The results are presented below in Table 32.

Table 32 indicates that 45 mph I-17 SB and US 89 do not have statistically different R values. At 65 mph there is no statistically significant difference between the R value in the three beds.

TABLE 32 TWO-WAY LEAST SQUARES MEANS (SPEED*BED), AND PAIRWISE COMPARISONS FOR ALL RUNS EXCEPT SR 77: RESPONSE VARIABLE R

Pop. Cell Mean	*Least Squares Means*	*Std. Errors*	*45 US 89*	*45 I-17 NB*	*45 I-17 SB*	*65 US 89*	*65 I-17 NB*	*65 I-17 SB*
45 US 89	0.274	0.0046		0.7779	**0.0001**	0.1292	0.1750	0.3276
45 I-17 NB	0.276	0.0041			0.0001	0.1877	0.2548	0.4495
45 I-17 SB	0.239	0.0046				0.0001	0.0001	0.0001
65 US 89	0.284	0.0046					0.8049	0.6231
65 I-17 NB	0.283	0.0041						0.7800
65 I-17 SB	0.280	0.0049						

Comparison Across Beds

The analyses presented so far have not included a comparison across all beds. One of the analysis by Dr. Burdick included the I-17 NB, I-17 SB, and US 89, but not SR 77. This was because SR 77 had only one type of bed preparation. If one of the beds used for the "all except SR 77" was similar to SR 77 in some respect, it could be compared to SR 77. I-17 NB has a vertical curve of approximately the same length as SR 77 and has the same type of aggregate. I-17 SB had a large concave area at the beginning of the bed and US 89 has the smaller pea gravel.

The comparison between I-17 NB and SR 77 only includes the 65 mph Dozer preparation made in the Middle of the bed, as these are the expected conditions for actual entries. As Table 33 demonstrates a 206% increase in average depth yields an increase of 18.1 percent in average R value.

TABLE 33 COMPARISON OF I-17 NB AND SR 77

	Average Depth for 65 mph Smooth Runs (inches)	Average Stopping Distance (feet)	Average R
I-17 NB	12.8	415	0.343
SR 77	39.2	357	0.405

To further compare SR 77 with the other beds, a comparison of the effect of TRACK and SPEED was made. At SR 77 the average stopping distance for a Smooth bed was 279 feet compared to a stopping distance of 316 feet for a Tracked bed. This represents a 13 percent increase from Smooth to Tracked. For the data used in the "all except SR 77" analysis, the percent increase was 14 percent. At 45 mph the average stopping distance for SR 77 was 223 feet compared to 372 at 65 mph which is a 67 percent increase. For the "all except SR 77" data, the increase in stopping distance from 45 mph to 65 mph was 74 percent. Therefore, with respect to SPEED and TRACK, the SR 77 data appears consistent with the other beds.

Figure 26 shows all of the 102 data points used in the statistical analysis. Regression lines are superimposed on the figure for each of the arrestor beds. Since Speed was used at two levels in the experimental design, the data are clustered about 45 and 65 mph. Development of a regression model from this arrangement of data can lead to errant conclusions if interpolations or extrapolations of the data are performed, so the equations are presented as a means to demonstrate trends in the data rather than as models that can be used for arrestor bed design. For example, one of the questions that must be addressed is the R value for design. Figure 26 demonstrates that the minimum R observed during the experiment was 0.25 g. Futhermore, at each of the arrestor beds, R increases with increasing speed. This suggests that using 0.25 for design is very conservative. The difference in the slope of the regression lines for each of the arrestor beds indicates the interaction between BED and SPEED. US 89 is the least sensitive to speed while SR 77 demonstrates the greatest dependence.

EVALUATION OF THE TIME VS. VELOCITY DATA

The time vs. velocity plots were obtained using the data acquisition developed by the ASU research team. All available plots are contained in Appendix B. In evaluating the plots it is important to remember that a 3-S-2 vehicle with an approximate front to rear axle spacing of 50 feet will require approximately 0.52 seconds for a 65 mph entry speed, and 0.75 seconds for a 45 mph entry speed, before all the wheels are in the gravel. The PTI work (11, 12, 13) has claimed to have observed a phenomena they call "planing", which can be described as riding on top of the gravel for period of time before the wheels sink into the gravel. An inspection of the time vs. velocity plots in Appendix B might suggest a planing effect, however, if the plots are evaluated after all wheels have entered the gravel, the effect is greatly diminished.

Questions about the effect of bed depth, and grade have been part of this research. One of the original ideas for analyzing the time vs. velocity plots was to see if the deceleration changed when the

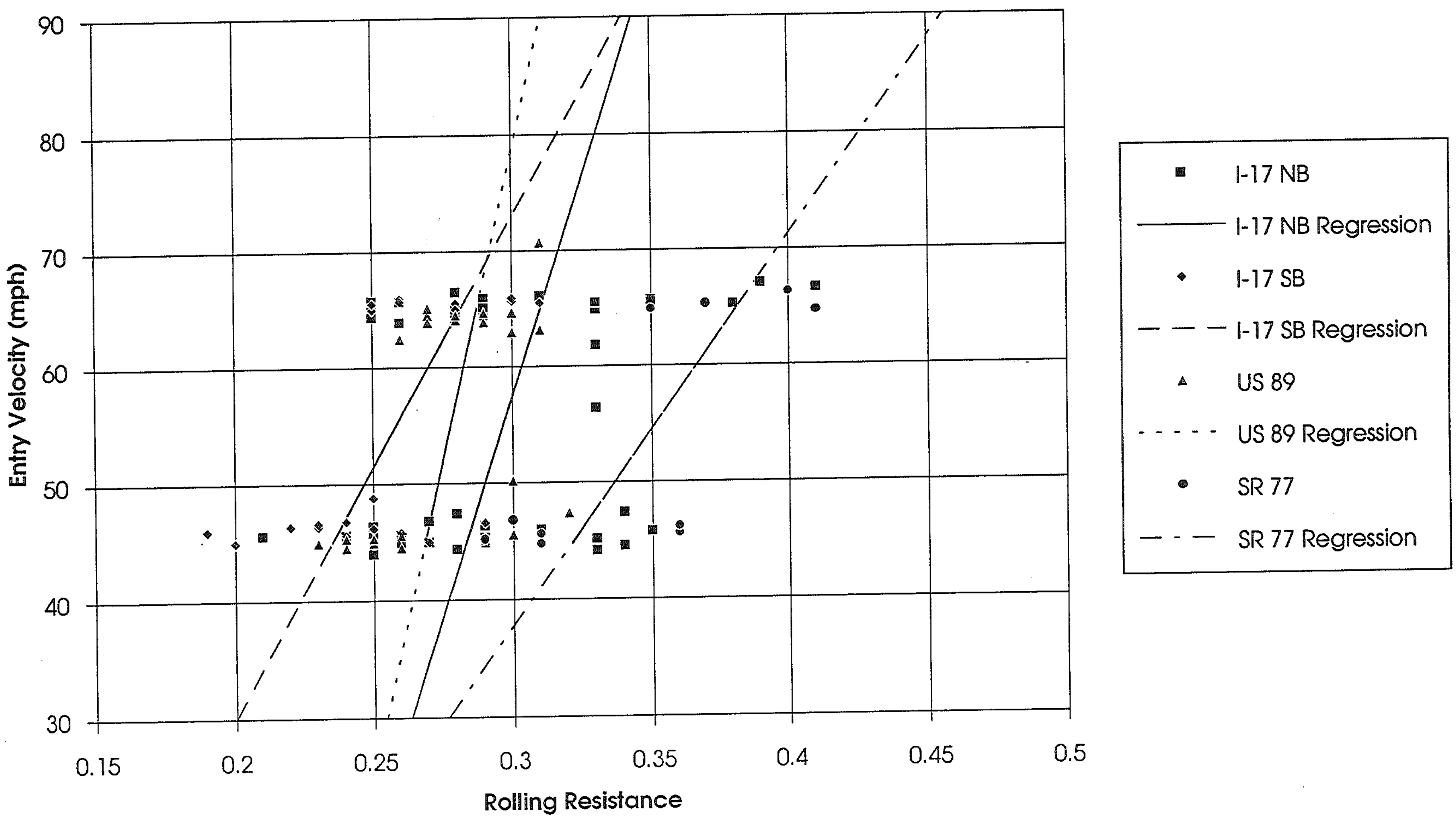


FIGURE 26 SUMMARY OF ALL ARRESTOR BED TESTS

vehicle entered a deeper part of the bed. This, it was hoped, would give information about the effect of gravel depth on R. The problem with this approach is that there are either two or three, depending on whether the bed has vertical curve at the beginning, covariants as the truck traverses the length of the arrestor bed: 1) speed, 2) depth, and 3) grade. As the speed decreases, the depth increases in all cases. In beds with vertical curves, the grade will decrease initially with speed then increase.

The majority of plots in Appendix B, with the exception of I-17 SB, indicate a relatively linear relationship between velocity and time after all wheels of the truck have entered the bed. At I-17 SB the non-linearity was attributed to the concave area at the beginning of the bed. Hence, the relative increase in bed depth was greater for I-17 SB. To assist with a subjective evaluation of the plots a regression line has been superimposed onto the radar data.

Regression of Field Data

Regression was performed on time vs. velocity observations measured during each run. These data are not independent and therefore a regression model would not be appropirate for predictions. However, the regression can be used to test for linearity. The regression was begun after all wheels entered the bed and the noise at the end of the run (Figure 22) was removed . Figure 27 shows an example of the results.

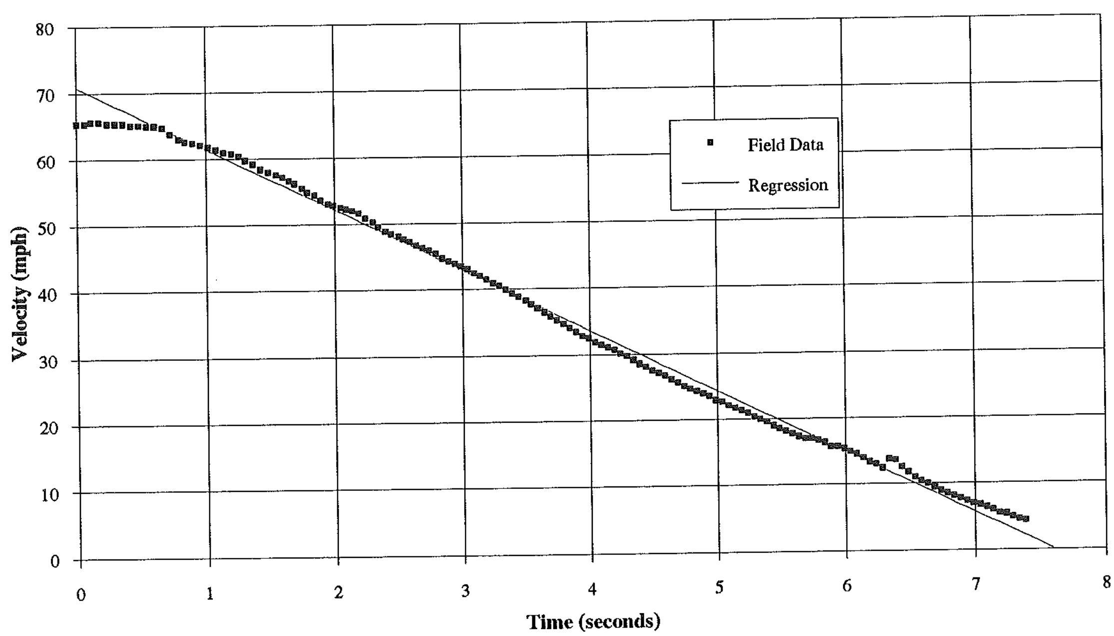


FIGURE 27 I-17 NB RUN NUMBER 10 (1991) DOZER, SMOOTH

The R^2 value for the above regression is 0.998 and the equation of the line is $V = -9.64\ t + 71.72$ where V is velocity in mile per hour and t is time in seconds. The deceleration rate of the linear portion of the run can be calculated by converting the slope into feet per second squared and dividing by the acceleration due to gravity. The deceleration corresponding to the linear portion of Figure 27 is 0.44 g's. The back-calculated deceleration reported in Table 7 is 0.38 g's. The discrepancy arises because the regression line does not account for the time it takes for the vehicle to fully enter the bed. The area under the curve corresponds to the distance of the run. The area under the regression line indicates a stopping distance of 394.73 feet. The actual stopping distance was 378 feet. The resulting error between the regression approximation and the actual stopping distance is 4.5 percent on the conservative side.

Suggested Equation

PTI has recommended a third order regression equation to model the distance a vehicle will travel in an arrestor bed. The testing conducted here has indicated that the character of the time vs. velocity relationship is linear after the vehicle has fully entered the bed. The design equation that ADOT currently uses assumes a linear velocity-time relationship. The only modification that could possibly make the design more realistic is to add a term to the equation that represents the wheel base of the design vehicle and use the actual deceleration in g's for R in equation (1). Appendix B contains the available time vs. velocity plots. The deceleration in ft/s^2 is given for each plot. These values would have to be adjusted to account for the difference between the grade of the beds in the plots and the grades of the bed being designed. Although this approach would represent a step toward a more realistic design equation, it appears that the current design approach is more reasonable. Therefore, the continued use of the current design equation is recommended.

Summary

The time vs. velocity plots with the regression line superimposed offer a unique and easy subjective way to evaluate linearity of the time vs. velocity relationship of a vehicle entering an arrestor bed. The time vs. velocity plots presented in Appendix B indicate the deceleration is constant as Jones (8) had assumed and is implicit in equation (1) used by ADOT to design arrestor beds. A modification to

ADOT's current design equation was evaluated to more accurately model an actual runaway truck event in an arrestor bed. However, the current design equation appears more practical at this time and is recommended.

CONCLUSIONS AND RECOMMENDATIONS

This report documents the performance of Arizona arrestor beds under specific conditions. The main conclusion is that Arizona arrestor beds have performed their intended function of bringing the vehicle to a safe and controlled stop. The only protection that was used for the test vehicle was Plexiglas on the windshield and headlights, and a rubber mat to protect the radiator. No significant damage was sustained to the test vehicle.

The other conclusions reached are:

1. R generally increases with entry velocity. This may be due to increase in average gravel depth for longer stopping distances.
2. Tracking decreases the R value an average of 14 percent. The effect is mostly due to decreased aggregate depth but could also be partially explained by aggregate reorienting into a denser configuration upon wheel loading.
3. The tracking effect diminishes with successive entries into the same tracks. For the "double tracked" runs the average initial decrease in R was 24 percent, while the decrease due to an additional entry was 5 percent.
4. Bed preparation equipment has a significant effect on the performance of arrestor beds. Equipment that scarifies the bed produces significantly higher R values and shorter stopping distances that a type of equipment that only levels the bed.
5. The side effect had a statistically significant effect on R and therefore the distance traveled. This is probably due to a combination of variation in grade, depth, and edge effects of the access roads.

6. Most of the beds have developed a depression about 50 feet from the arrestor bed beginning due to aggregate spray that occurrs as the result of arrestor bed entries. In most this cases the depression is almost imperceptible to the human eye.

Recommendations

Recommendations, based on a review of the literature, observations during the testing, and analysis of the data are as follows:

1. The depth of gravel of 24 inches is more economical than a gravel depth of 48 inches. An average gravel depth of 12.8 inches in the I-17 NB bed produced a mean deceleration for the 65 mph Dozer Middle preparation of 0.34, while for the same conditions an average gravel depth 39.2 inches produced a mean declaration of 0.41 in the SR 77 bed. The volume of aggregate, assuming a 40 foot wide, level grade arrestor bed, using equation (1) with a 90 mph entry velocity and a 48 inch deep bed, configured such that the average depth was 39.2 inches for the 667 foot stopping distance would be 87,155 cubic feet. The volume for a bed of the same width and slope, using equation (1) with a 90 mph entry velocity, assuming an average depth of 15.8 inches over the 787 foot stopping distance would require 33,579 cubic feet of aggregate. This represents a 61 percent reduction in aggregate volume. Earth work associated with the additional 120 feet in length would need to be considered against the cost savings in aggregate.
2. The transition from initial depth to final depth should be no greater than 50 feet for an arrestor bed with a maximum depth of 24 inches. The purpose of the transition is to permit a gradual deceleration of the vehicle as it enters the bed. Data from SR 77, with the greatest depth gradient, did not demonstrate any problem with excessive deceleration rate.
3. The gravel should be an uniformly graded river run aggregate of either the original specification, the revised specification, or anything in-between. This conclusion can only be based on the data collected during this research. Other factors that could affect the selection of an aggregate, such as contamination due to wind blown silts could not be evaluated during this research.

4. Arizona arrestor beds exhibit an approximately linear relationship between velocity and time once all wheels are in the bed and therefore equation (1) should be used. The minimum R value experienced in all the 65 mph runs was 0.25. This R value at 65 mph generally represents the tracked condition which may be experienced by runaway vehicles due to the response time required for ADOT crews in remote locations. Because the R value tends to increase with higher speeds due to grade and depth effects, R=0.25 would represent a conservative design approach for 24 inch deep beds. This value could probably be increased if the transition length were decreased. The design R value of 0.25 should definitely be increased when the depth is greater than 24 inches.
5. Some type of grade control should be retrofitted onto the beds to help maintenance workers maintain the design arrestor bed grade and thickness. This would help to prevent the type of depression or concavity observed at I-17 SB. The grade control could easily accomplished by placing flexible delineators of a given height by the side of the bed. Then one maintenance worker could operate the bulldozer while the other used a lock-level and an engineers rule to check the grade.
6. The beds should be scarified after each run or periodically. The only equipment type used in this testing program that worked satisfactorily was the bulldozer when it had rippers.

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APPENDIX

APPENDIX A: EXPERIMENTAL PLAN

Evaluation of Arrestor Bed Performance: Experimental Design

Step One.

Carry out confirmation runs (Design A) on I-17 NB.

Design A

	Preparation	Entry Speed
1.	smooth (dozer)	45
2.	tracked	45
3.	tracked	45
4.	smooth (dozer)	65
5.	tracked	65
6.	tracked	65
7.	tracked	65
8.	smooth (dozer)	65
9.	tracked	65
10.	smooth (dozer)	65
11.	tracked	65
12.	smooth (dozer)	45
13.	tracked	45

Step two.

Analyze results of confirmation runs. Do runs appear to come from the same distribution as the previous 10 good runs? If yes, follow design A1 for I-17 NB, if not, follow design A2 for I-17 NB.

Design A1

	Preparation	Entry Speed
1.	rake	45
2.	loader	45
3.	loader	45
4.	rake	65
5.	loader	65
6.	tracked	65
7.	rake	65
8.	tracked	65
9.	rake	65
10.	tracked	45
11.	loader	45
12.	tracked	45

Design A2

	Preparation	Entry Speed
1.	rake	65
2.	tracked	65
3.	loader	45
4.	tracked	45
5.	rake	45
6.	tracked	45
7.	loader	65
8.	tracked	65
9.	dozer	45
10.	tracked	45
11.	loader	65
12.	tracked	65
13.	rake	45
14.	tracked	45
15.	loader	45
16.	tracked	45
17.	rake	65
18.	tracked	65

Step Three.

Carry out the following 24 runs (Design A3) on I-17 SB.

Design A3

	Preparation	Entry Speed
1.	dozer	45
2.	tracked	45
3.	rake	65
4.	tracked	65
5.	loader	45
6.	tracked	45
7.	dozer	65
8.	tracked	65
9.	rake	45
10.	tracked	45
11.	loader	65
12.	tracked	65
13.	dozer	45
14.	tracked	45
15.	loader	65
16.	tracked	65
17.	rake	45
18.	tracked	45
19.	loader	45
20.	tracked	45
21.	dozer	65
22.	tracked	65
23.	rake	65
24.	tracked	65

Step Four.

Analyze the data to determine if the data are showing any particular patterns that should be investigated in particular on future runs. Revise the workplan if appropriate.

Step Five.

Do the 24 runs of Design A3 on US 89.

Step Six.

Analyze the data gathered in step five. After the analysis of the data in steps three and five, it should be possible to make a decision on the best preparation type for each bed. This decision will be make based on cost, time and effectiveness. It is possible that the best preparation method can only be narrowed down to two of the three or that the data is inconclusive.

Step Seven.

Choose SR 68 or SR 77 for the next test site.

Step Eight.

Carry out Plan A, B, or C based on the analysis done in step six on the site chosen in step seven.

Plan A: Use this plan if the analysis in step six showed a clear winner for the best type of preparation for this material type. Do the 8 runs of Design A4 for tracked and the best preparation.

Design A4

	Preparation	Entry Speed
1.	preparation	45
2.	tracked	45
3.	preparation	65
4.	tracked	65
5.	preparation	65
6.	tracked	65
7.	preparation	45
8.	tracked	45

Plan B: Use this plan if the analysis in step six indicated that two preparation methods were equal and superior to the third. Do the 16 runs of design A5 for tracked and the two best preparation methods.

Design A5

	Preparation	Entry Speed
1.	type 2	45
2.	tracked	45
3.	type 1	65
4.	tracked	65
5.	type 1	65
6.	tracked	65
7.	type 2	45
8.	tracked	45
9.	type 1	45
10.	tracked	45
11.	type 2	65
12.	tracked	65
13.	type 1	65
14.	tracked	65
15.	type 2	45
16.	tracked	45

Plan C: If there is no conclusive evidence on preparation type, do the 24 runs of Design A3.

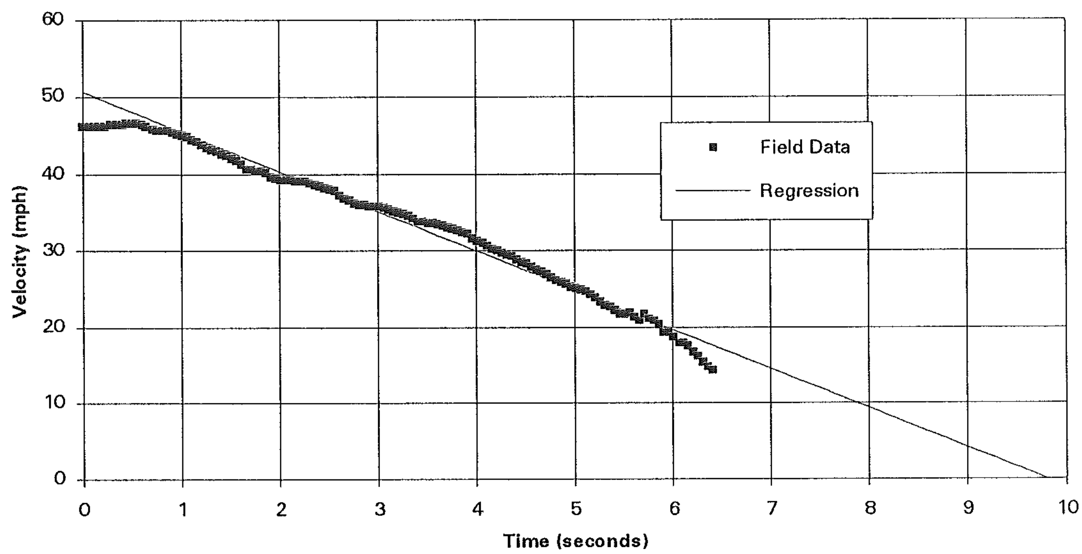
Step Nine.

Evaluate the data. At this point there should be conclusive evidence for the best preparation type. Note that the preparation type could vary depending on the material (US 89 versus the other beds). The depth factor should be evaluated at this time.

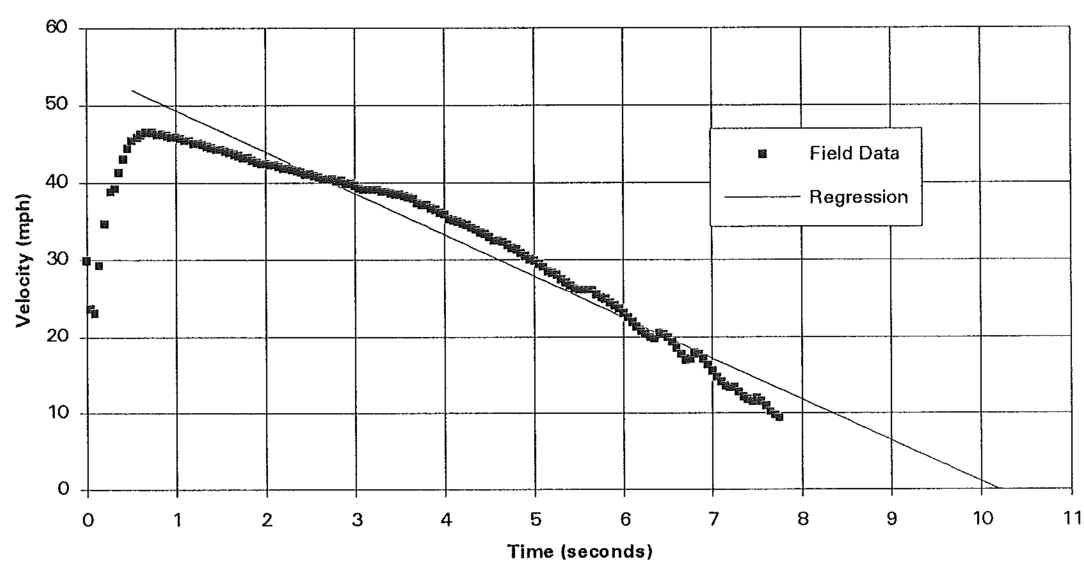
There should also now be enough evidence to make good estimates on entry distance relative to entry speed based on the depth of the bed.

After a complete analysis, a decision should be made on any further testing.

APPENDIX B: TIME VS. VELOCITY PLOTS



I-17 SB Run #1, R^2=0.986



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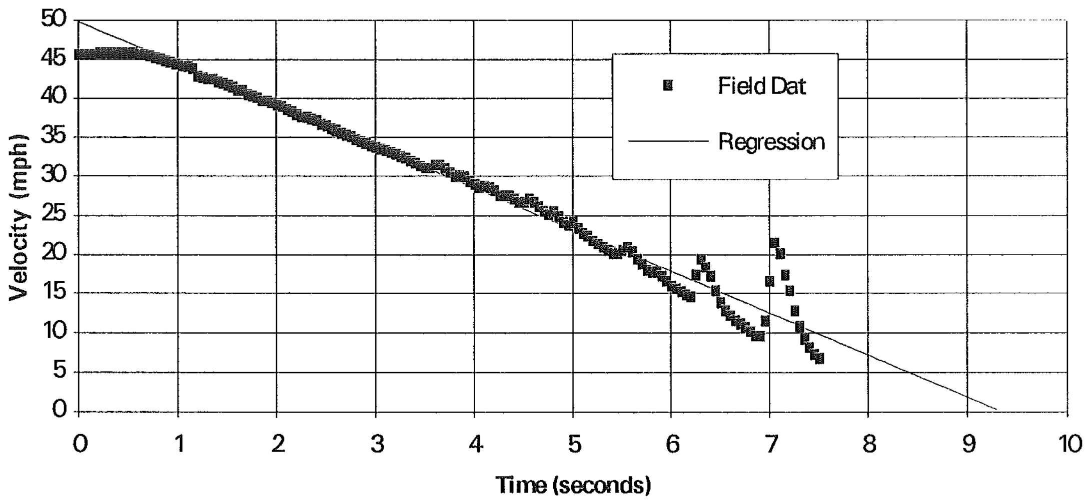

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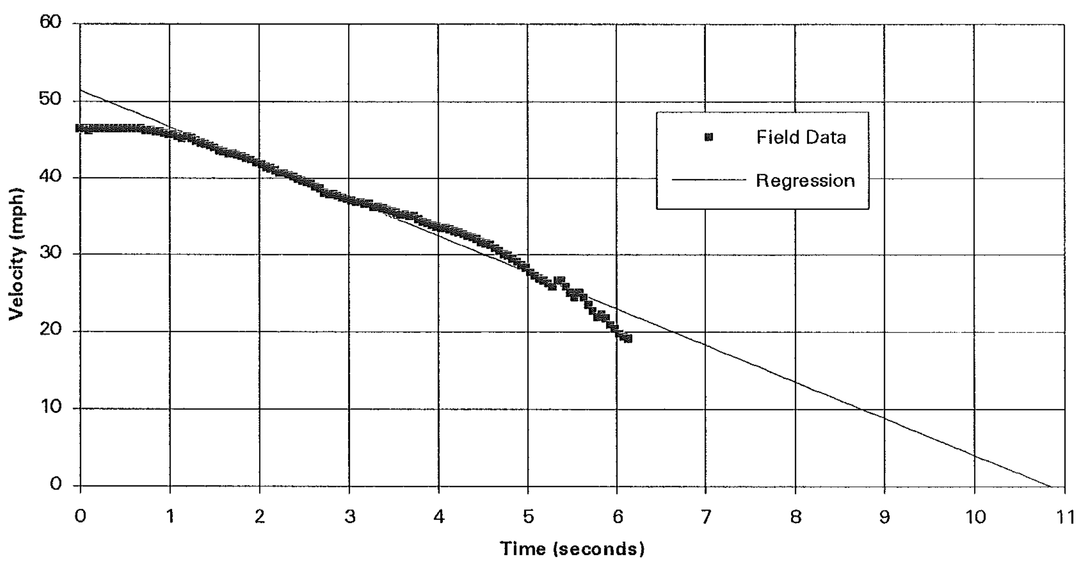

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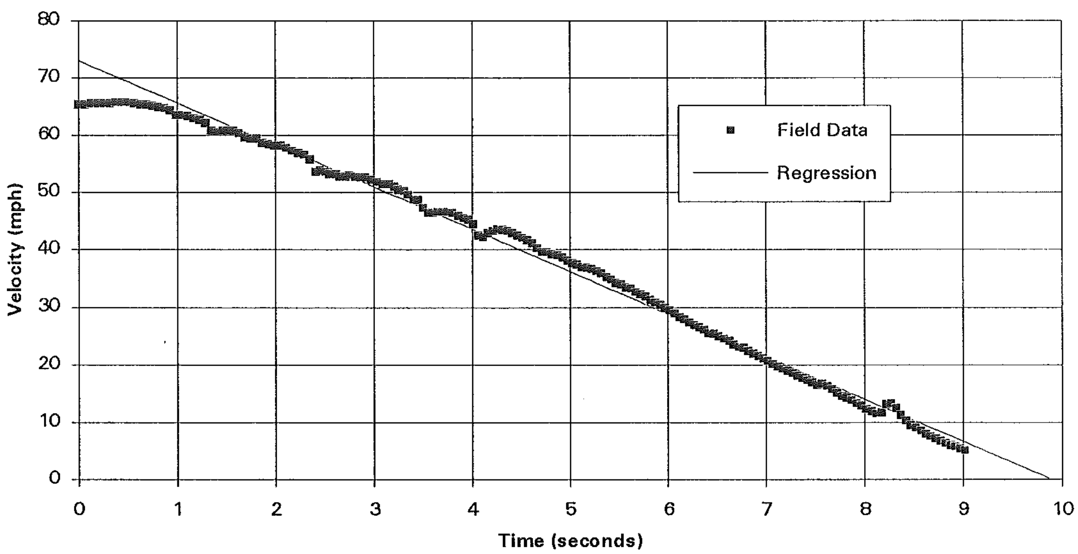
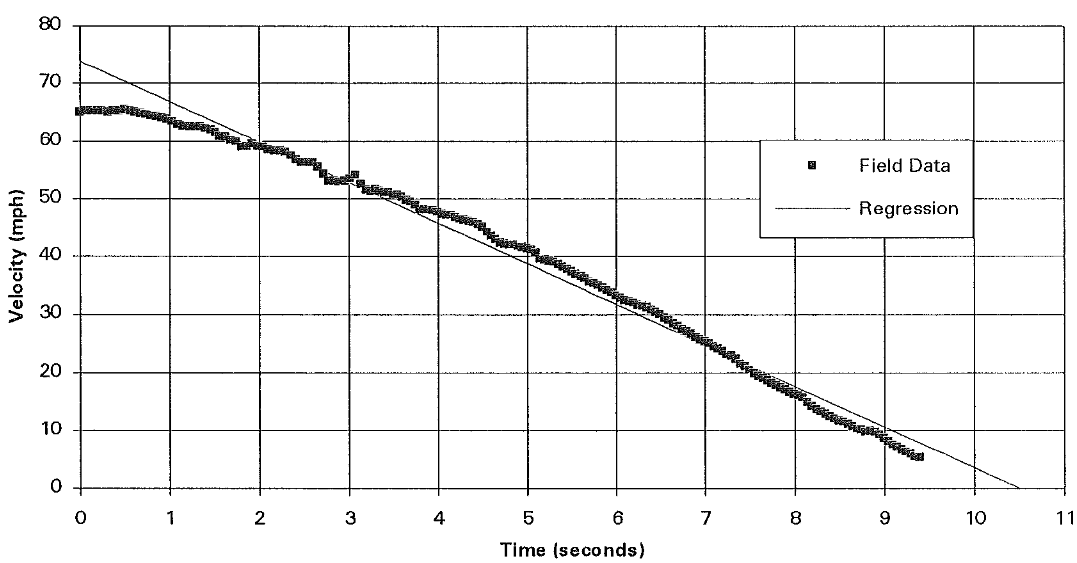
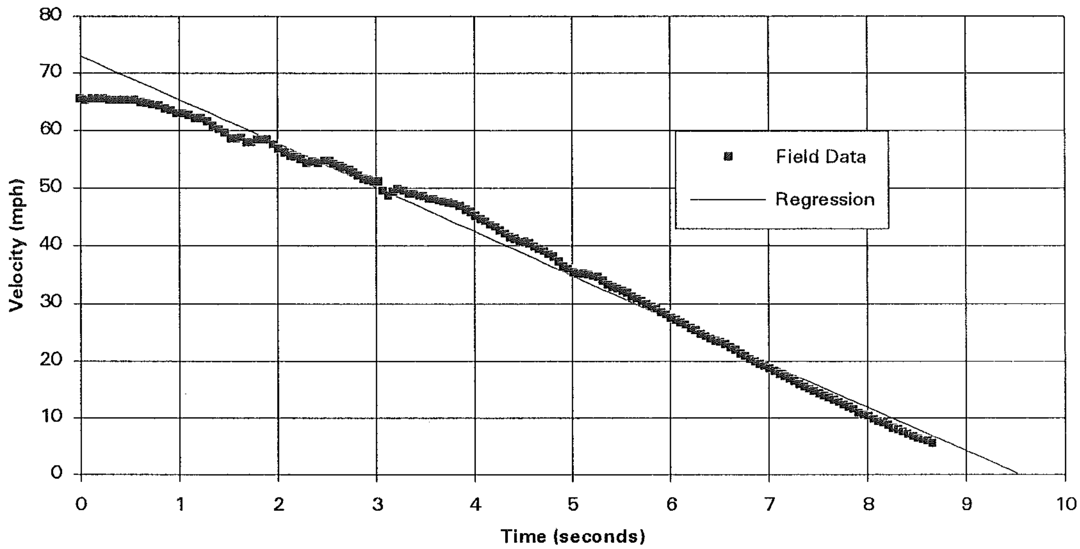


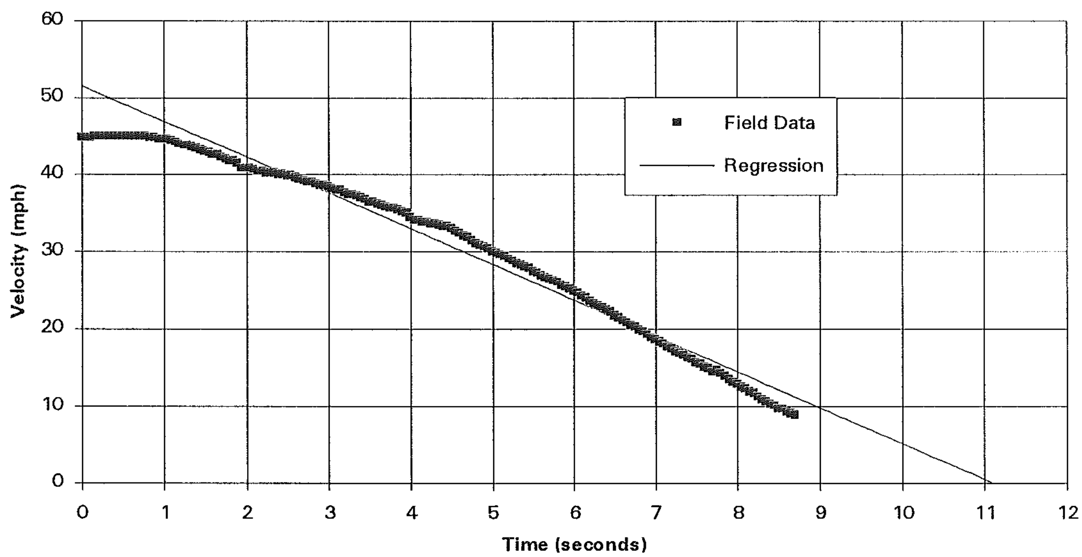
I-17 SB Run #5, R^2=0.995



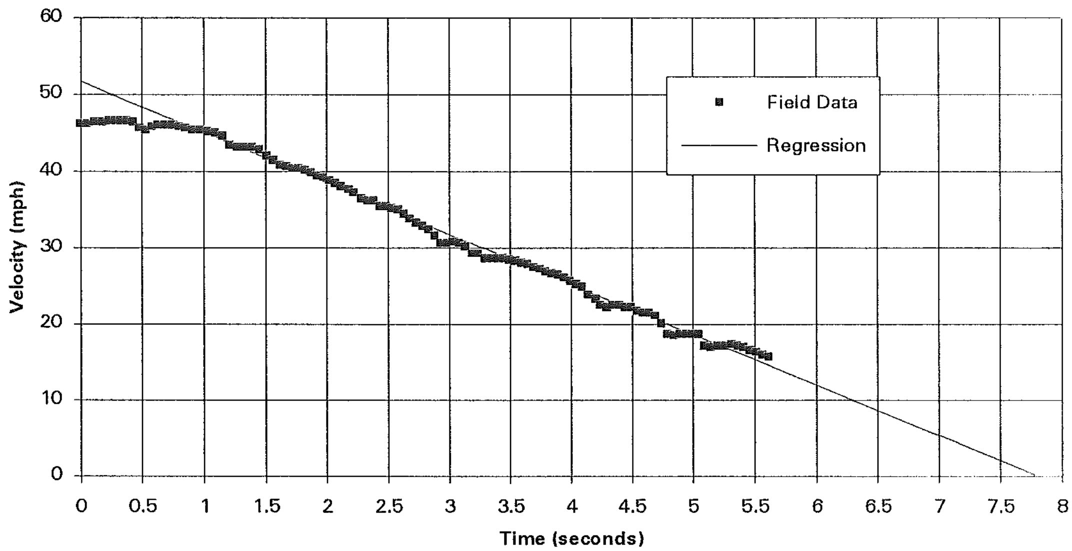
I-17 SB Run #6, R^2=0.988



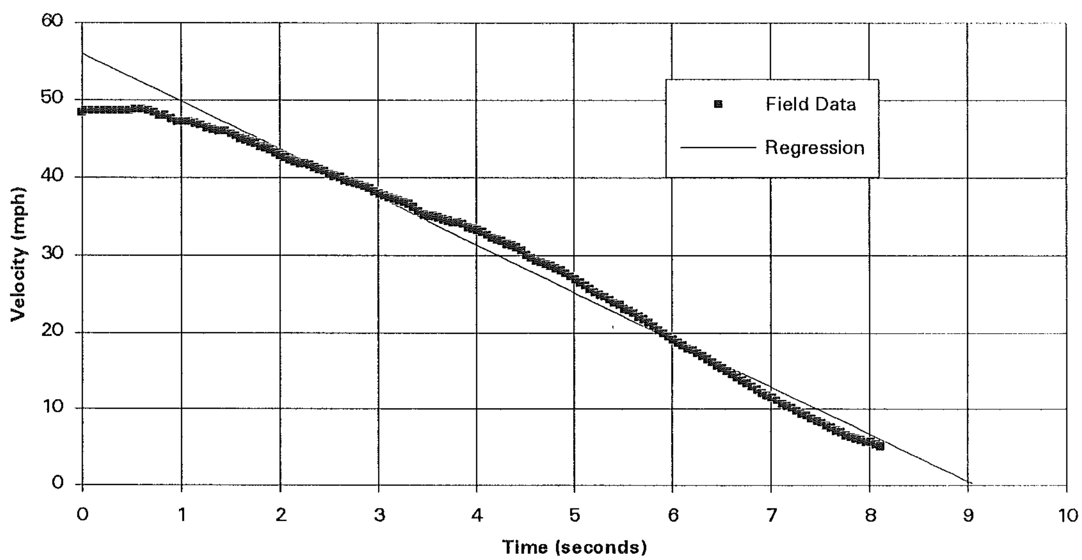
I-17 SB Run #7, R^2=0.992



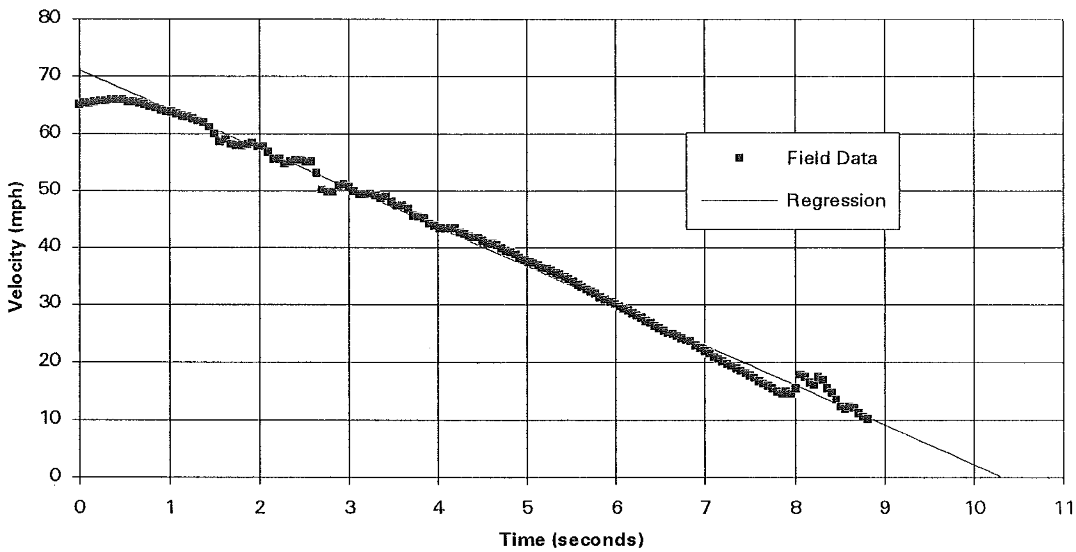
I-17 SB Run #9, R^2=0.981



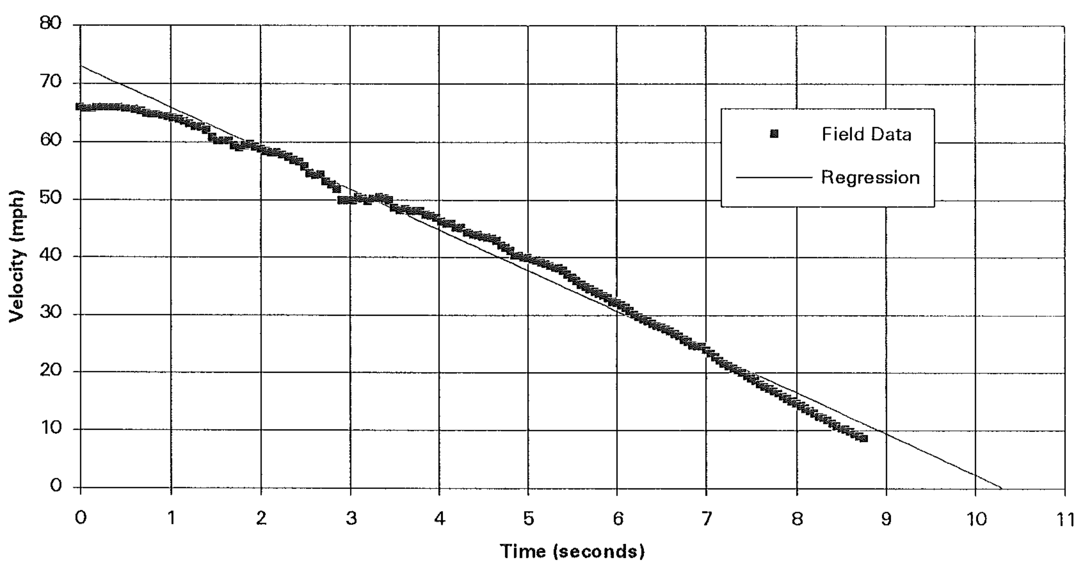
I-17 SB Run #10, R^2=0.996



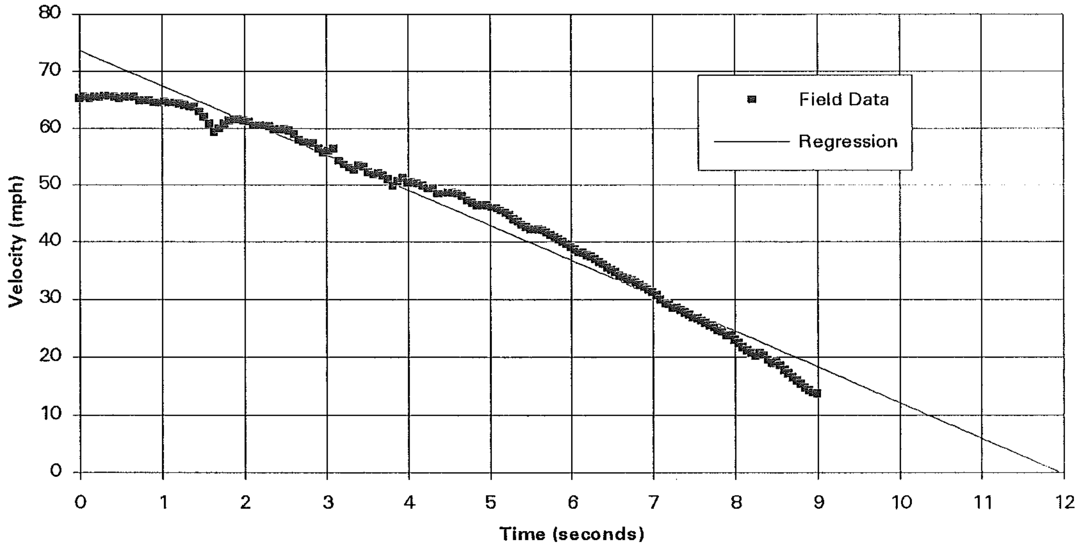
I-17 SB Run #11, R^2=0.989



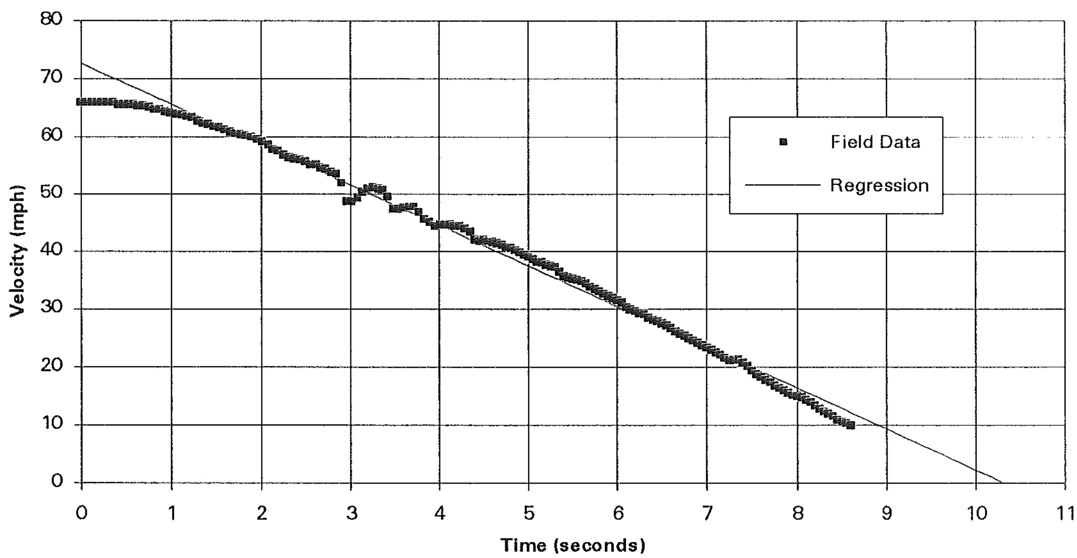
I-17 SB Run #12, R^2=0.995



I-17 SB Run #14, R^2=0.990



I-17 SB Run #15, R^2=0.979



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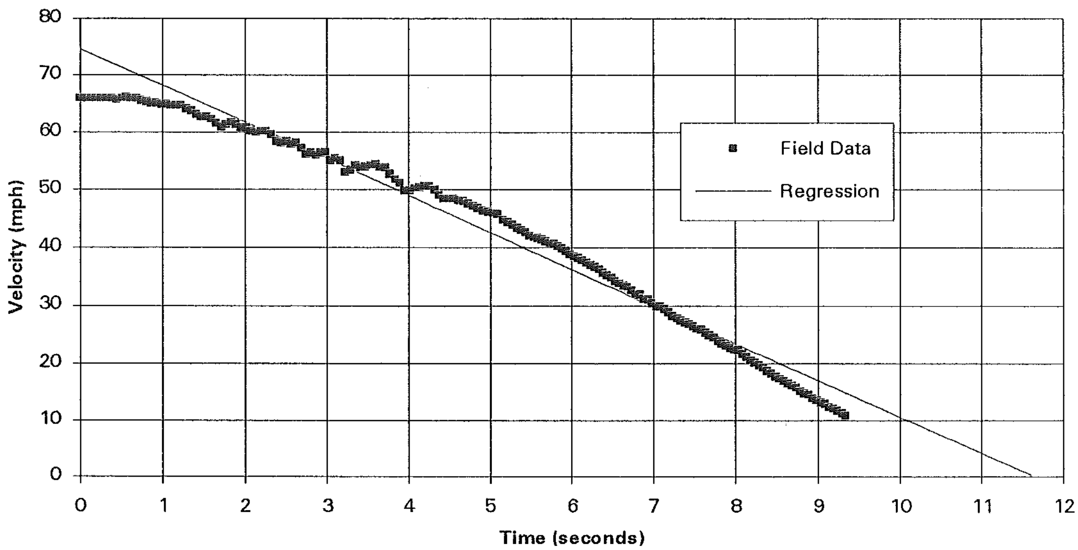

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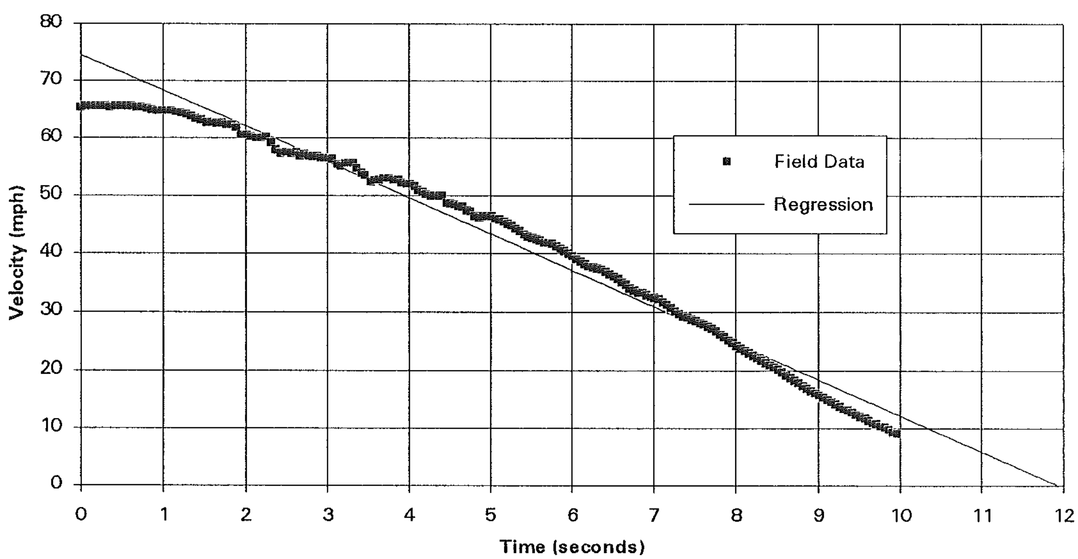
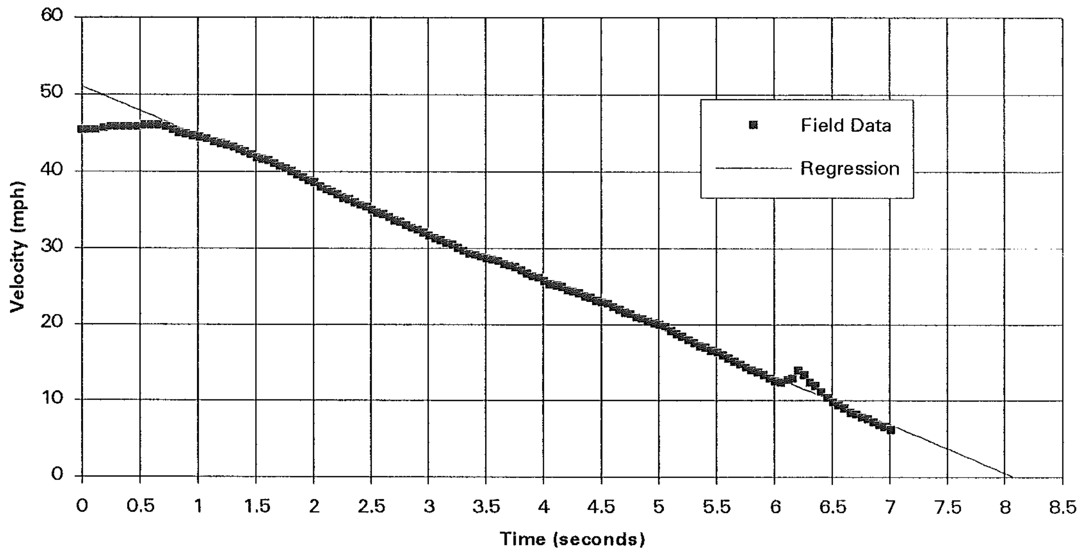


I-17 SB Run #19, R^2=0.982



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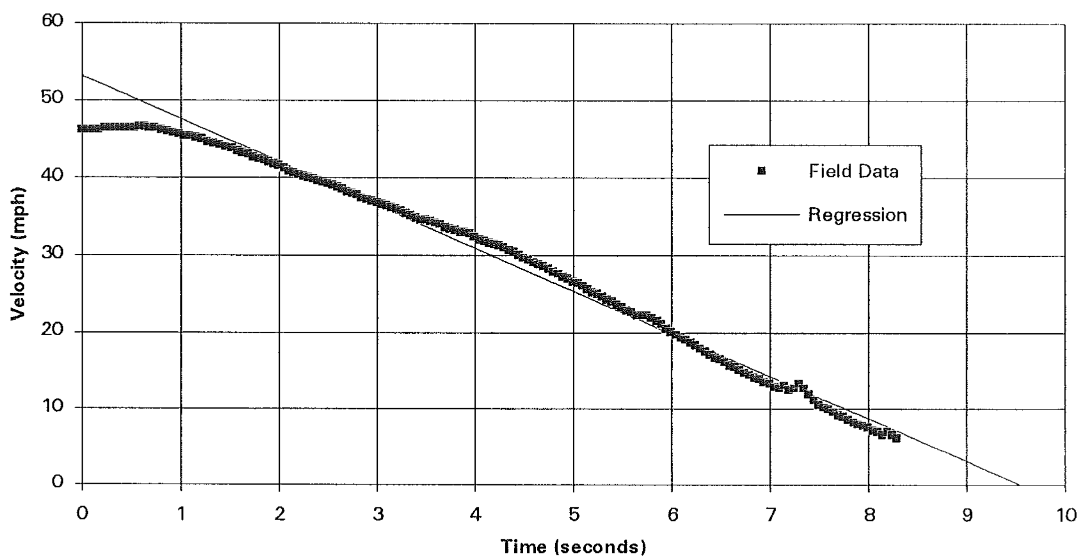
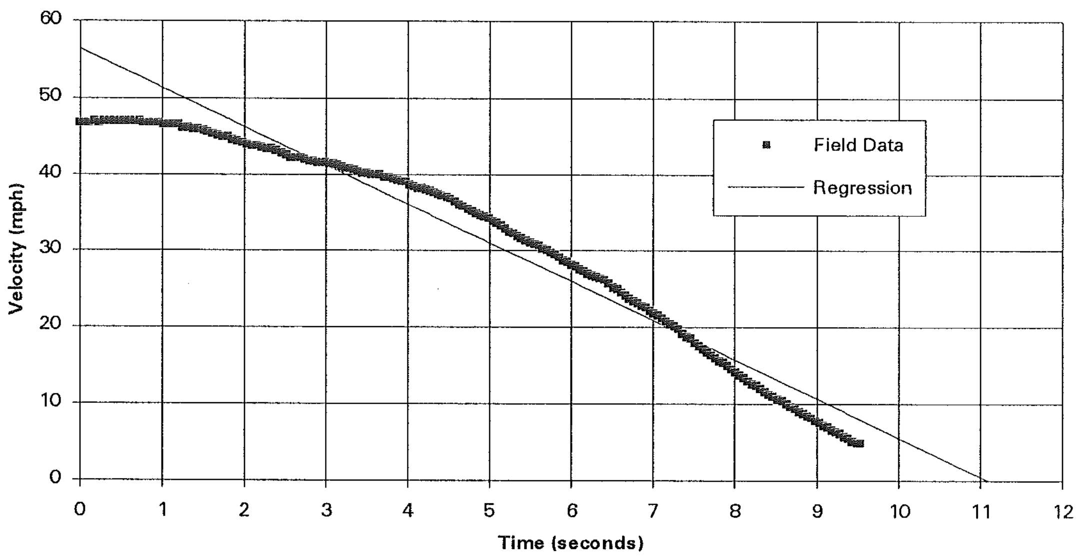


I-17 SB Run #21, R^2=0.992



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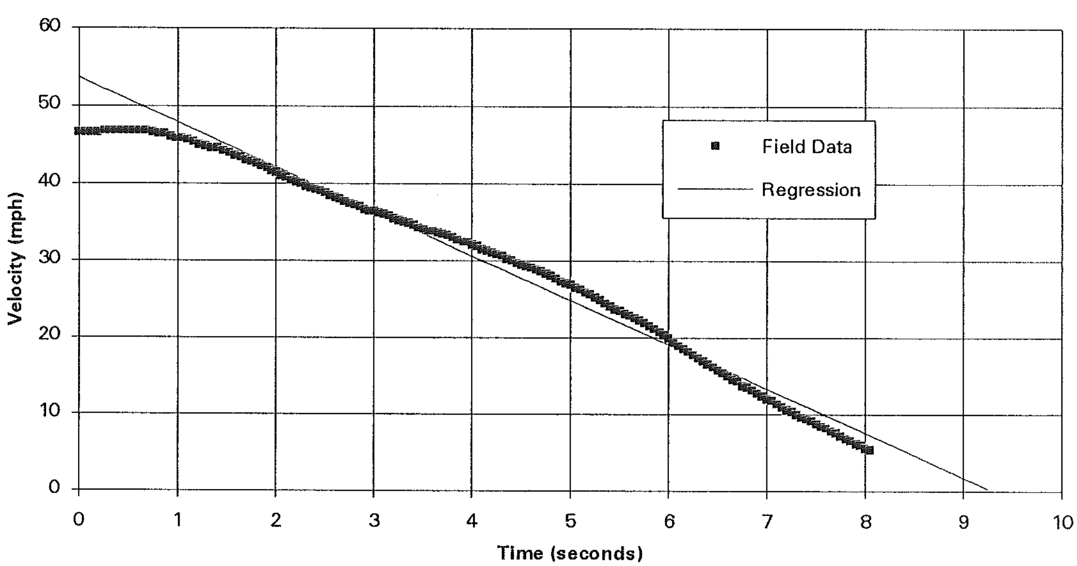

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